Constructing the Seismometer

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Abstract

Future generations of gravitational wave measurements will be polluted with Newtonian noise. For studying this noise, the ultimate goal of being discovering how to subtract it, seismometers are used at the former Homestake mine in Lead, South Dakota. A problem with seismometers is that these are designed for high sensitivity at low frequencies of which wave measurements are not concerned. To obtain a seismometer that has better sensitivity at higher frequencies (1-30 Hz) the SS-1 Ranger has been looked at and its parts designed on AutoCAD for sensitivity at 1-30 Hz and modifications made for less mechanical and electrical noise.

I. Introduction

It is anticipated Newtonian noise will limit the gravitational wave measurements of future gravitational wave detector (GWD) generations [2], thus making it desirable to find a way to subtract this noise from such measurements. Little is known about NN [2,9], but its effects in GW studies want to be minimized. This noise is studied with seismometers in the depths of the former Homestake mine in Lead, South Dakota where noise is a factor of ten less than above ground [2], making it a potential spot for a future GW detector as well if it is shown subtraction and filtering noise is done much easier here [2,5,9]. Problem is; seismometers are not designed to study this noise, as too much electronic and mechanical noise from these mixes in with the data [2]. The proposed solution is to build a new seismometer.

To do so a SS-1 Ranger (Figure 1) was dissected to construct a seismometer modeled off it [2]. When dissecting it, it was noted how surprisingly simple its design is. At its core is a test mass of cylindrical shape. The mass has a circular magnetic strip around it and a spring passing through its center. On top of the mass there is a rod, and when the mass moves the rod moves. Through its design, more of which is discussed in Section II, a titled mirror is placed in a spot where the rod passes by when it moves. This mirror, along with a readout at the top of the mass and a calibration coil below it, determine how far the mass has moved and send the information to a readout system.

Figure 1: The SS-1 Ranger.

Using drawings and measurements of the seismometer, AutoCAD is being used to model the Ranger's components with the best precision the program allows. These designs are the beginning of a bigger project in which, ideally, a seismometer is constructed with excellent sensitivity in the range of 1-30Hz for NN study, since NN will be a major limiting factor of GWD's in this frequency range.

II. Dissection of the Seismometer

Newtonian noise is a direct result of seismic fields [2,6]. Seismic fields create perturbations in the ground causing the ground to displace ever so slightly on the vertical and horizontal axis [2]. This creates a change in density around a test mass which changes the gravitational field, the result being a force displacing this test mass along the horizontal axis a very small magnitude. This displacement is NN [2].

The former Homestake mine in Lead, South Dakota is an ideal location for studying this noise. Reaching depths of 4100ft for scientific study, the mine contains less seismic noise, and thus NN, than above ground [6]. Using a test mass system, a seismometer takes the distance a test mass is displaced in result of seismic fields and converts it to an electrical signal [2]. This signal is put through a readout system where it undergoes amplification before being recorded [2]. Using the electrical signal and simple result of how far the test mass was displaced, NN is then modeled [2].

Currently, there are 8 seismometers at Homestake in a 2D array which will soon be reconstructed into a 3D one [3] with the goal of figuring out the origins of NN [2]. These origins would be where the perturbations begin to affect a test mass noticeably. An understanding of how the density and gravitational field around a test mass change would then be possible, and with this predictions of how the test mass will shift with change in the gravitational field will develop [2]. If NN could then be understood at all frequencies, these predictions would permit subtraction of the noise from GW measurements [2]. Future generations of GWD's will use frequencies around 1-500Hz, with NN being a major noise source below 20Hz, so understanding NN at this frequency and close by frequencies is necessary as it will mix with the data, and with no way to subtract it out, the data will be difficult to analyze [2]. The seismometers used at Homestake, however, are not sufficiently sensitive to study seismic noise at Homestake and must be modified [2]. Only then will seismic fields, and in result NN, be understood at these frequencies [2].

The proposed solution to this problem is building a new seismometer. A new readout system has been designed on ExpressPCB [4] and will be tested for efficiency when acquired. More recently, the seismometer titled the SS-1 Ranger has been dissected with pictures taken, diagrams drawn, and component measurements made.

The design for the Ranger is rather simple. It contains an outer can around the sides/bottom and a top shell (Figure 1 shows both connected. In Figure 2, the top shell has been removed and is seen in the background).

The can is 131.4x140.2mm and has 6 screw holes at its top that connects to the top shell for complete, sealed enclosure when screws are put in. This can also has a metallic piece inside it at its bottom. This metallic piece is connected to a hatch like lever on the outside bottom of the can that is 38mm in diameter with a 6.3mm center piece and a height of 6.73mm. This lever allows one to loosen the inside so the rest of the seismometer can be taken out/put back in. It also has a hole with a spot to connect the wires in the seismometer to relay information to the readout system.

The top shell has two components: a bottom cylindrical ring and the narrow cylindrical ring (see the back of Figure 2 where this top shell is seen upside down). The bottom cylindrical ring is 130x12.6mm and goes 7.3mm inward before just having a hole of air (this neglects complicated surface changes, etc). There are 6 screws on it that connect to the bottom of the shell. It also has a 26mm glass ring allowing for one to look at the mass's rod move when the seismometer is closed.

The narrow cylinder is 45x135mm down to the big screw it contains to screw onto the bottom cylindrical ring described above and is 13 more millimeters deep with this.

When the top and outer/bottom shells are removed, it is seen there is a wood colored isolation cylinder surrounding the inside of the seismometer (Figure 3). The hallow isolation cylinder is 130x140mm and is 9.2mm inward. There are 6 spots for magnets on its edges (only 5 magnets were actually present when opened). It is predicted these magnets are an anti-spring system, as these are opposite sign the magnet around the mass, so these repel the mass from the edges of the seismometer so it does not touch the sides and make noise/become unstable

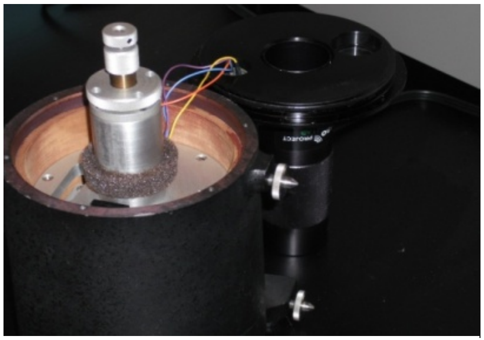

Figure 2: The Ranger with top taken off. In the back one can see the top shell and its two components screwed together.

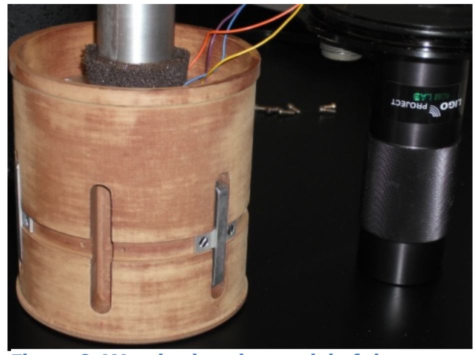

Figure 3: Wood colored material of the seismometer when the outer shell and can are removed.

After screwing it off and soldering the wires off of it that are attached above the test mass as well, the bottom of the isolation cylinder (this is called the isolation plate now) can be taken off and looks as seen in Figure 4. The image on the left focuses on the calibration coil. The yellow and pink wires are attached to it, and these, with the blue and orange wires connected to the readout coil at the top of the mass, along with the tilted mirror described earlier, measure the displacement of the mass and send it out as a signal to the readout system.

Figure 4: The bottom piece of the wood-like material; can be removed fully as in the first and second picture when the wires are soldered off.

An O-shaped flexure ring to keep the components aligned is attached to the bottom of the wood colored isolation ring and the magnet by two sliced trapezoid holders (Figure 5). One of the trapezoids allows for screws to be put in the wood colored piece, the other in the mass, thus attaching the flexture ring to these via the screws. The trapezoids are 30.1x8.72x7.6mm thick with a slice at 1.6mm. The flexure ring is 63.4x3mm and is olid 6.3mm inward (there is a flexure ring above the test mass as well.

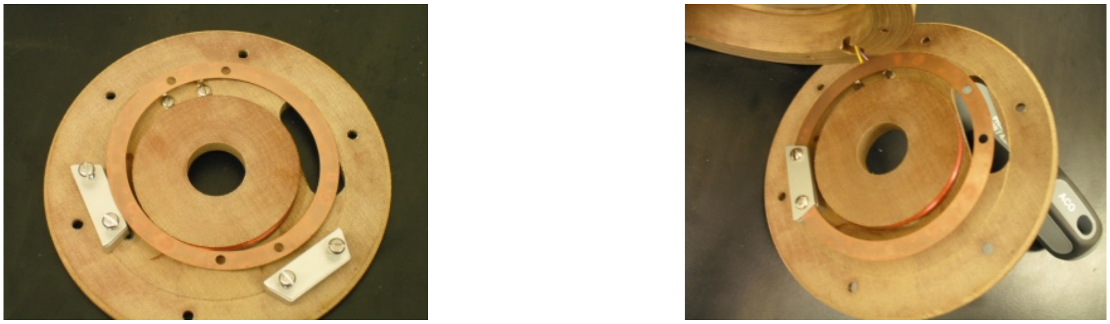

Figure 5: The flexure ring at the bottom of the seismometer (top one shown later). In a set of one of the holes is a trapezoid piece connected the flexure ring to the bottom part of the wood colored structure, and in the other is a trapezoid piece connecting it to the test mass.

Next is the 10kg test mass (Figure 6). It is 76x57.2mm. The magnetic strip is 38.2mm high and the parts that sandwich it are 9.5mm high. As Figure 6 shows, there is an outer and inner cylindrical shell making up the mass.

In the middle of the mass is a hole through which the spring of the seismometer passes. This hole is 15.6mm in diameter and goes all the way through the test mass. After this 15.6mm diameter, as seen from the top part of the mass, is a solid surface through which the test mass followed by a hollow point 41mm in diameter. This hallow portion goes all the way down to the start of the 9.5mm portion of the sandwich at the bottom of the mass and is then solid.

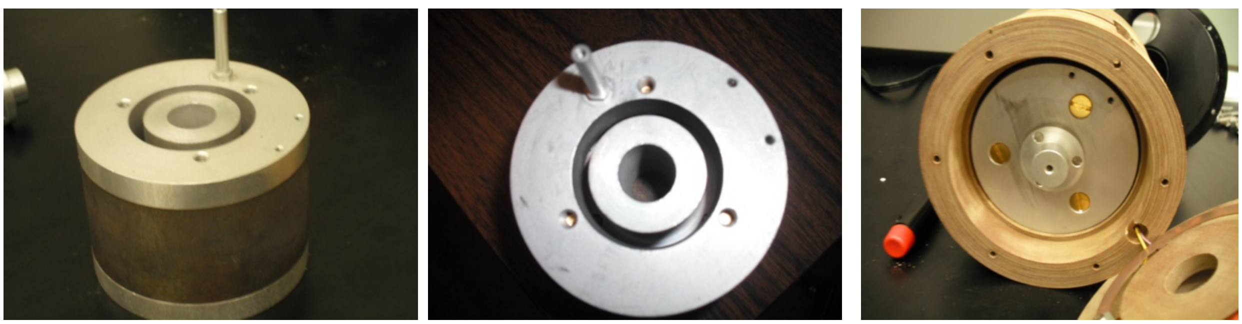

Figure 6: The test mass from the side, top, and bottom.

There is now the top portion of the test mass the screws are located on. It is 7.5mm from the edge of the mass to where this portion ends. The three bigger screw holes are each 60 degrees apart and 4.5mm thick. Each of these holes are 24.6mm from the center of the mass and each goes down to the bottom of the mass to where the brass screws are seen in the far right picture of Figure 6. The pair of smaller screws is 30 degrees apart from each other, 2.82mm in diameter, and 36.3mm from the center.

The rod is on top of a 2mm thick hexagon with side lengths of 3.3mm. The rod itself is 25.11mm.

On the bottom of the test mass are two of the same types of 2.82m screws in the same orientation. The larger hole are holes that connect to the three holes separated by 60 degrees on top and are in the same orientation, though now 4.5mm in diameter.

There are two other main sections of the seismometer to be measured: the system that contains the flexure above the test mass (Figure 7) and an elevated section that can screw off at the bottom of the test mass that holds the bottom of the spring.

While not all components of the seismometer have been measured, most have, and AutoCAD is being used to design three-dimensional models of these for later use when a better seismometer for the desired frequencies to understand NN at Homestake will be constructed.

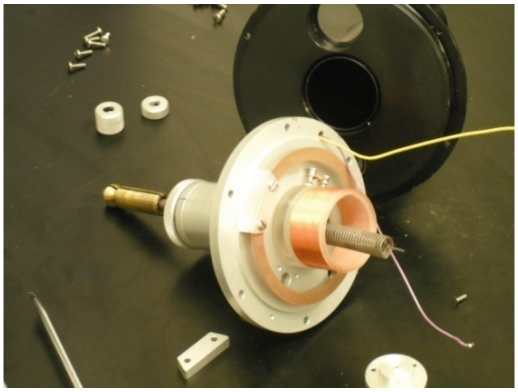

Figure 7: Section of the seismometer that is attached to the top of the test mass with the trapezoid figures as used at the bottom of the mass.

III. AutoCAD Designs

The main reason for dissecting the SS-1 Ranger was to get a better sense of how seismometers are constructed in terms of dimensions, types of components, materials, etc. With sufficient knowledge of these, one can design and construct a seismometer for the purpose one needs to use it for. So far many dimensions of the components for the Ranger have been made, as was seen in Section II. With these dimensions, 3-D AutoCAD drawings have been designed so the basis for the seismometer design can be looked at and altered as seen fit.

The first component to be modeled was the test mass. It took several attempts to model it successfully, as AutoCAD had to be learned and its quirks found and avoided. Placement of objects on the top, bottom, or inside other objects was rather tedious, but much has bene learned of AutoCAD during the designing.

The center of the mass, for simplicity, was put at 0,0,0, and other objects were placed at this coordinate and then moved around as needed in Cartesian and Polar coordinate system styles. The resulting modeled test mass is seen in Figure 8.

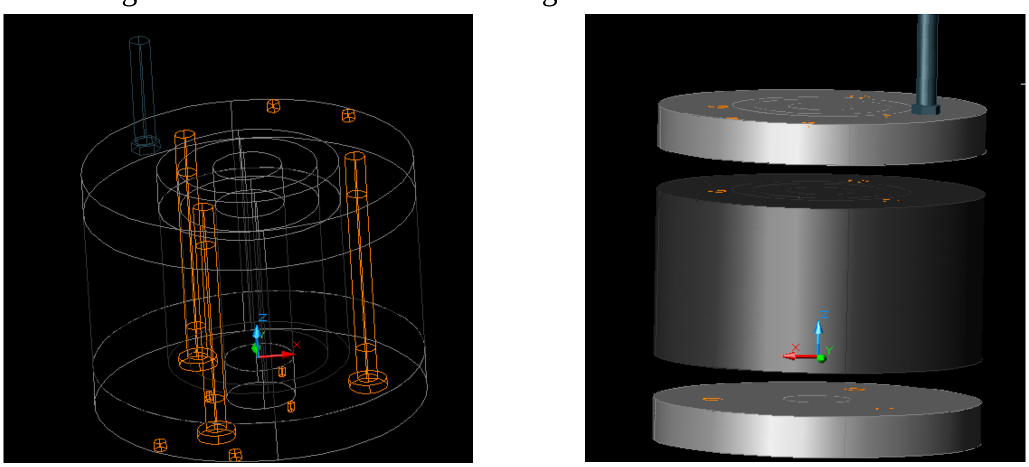

Figure 8: AutoCAD 3-D design of the test mass. The center of the test mass was placed at 0,0,0, which is the bottom and center of the black looking strip in the right hand figure. Each of the gray pieces that sandwich this is 9.5mm high and everything is placed based on Cartesian and Polar coordinates from there. Screws and the rod were mostly placed with Polar coordinates, and the other cylinders, as seen in the left figure, were placed with Cartesian coordinates. The tall, orange colored screws seen on the left figure were done in three parts, one for each segment (the 9.5mm gray pieces, and the gray piece that is not visible but right behind the black piece. This is because to make layers, as are done on this particular model, and to have successful subtraction afterwards where parts of the layers do not disappear for some reason, each component of the screw had to be attached to a particular layer. The hexagon that holds the rod was done by creating two trapezoids with subtraction of squares from squares and then adding the two hexagons together.

The flexure rings, flexure clamps, bottom plate, and wood colored isolation cylinder (not wood colored in the model, however) were also designed.

After calculating where each object goes in the overall design of the seismometer on Cartesian coordinates, each of the designed components will be put in proper place on one drawing. Advancements for other aspects of the seismometer will be made as well.

IV. Noise Curve and Future Plans

The design for the seismometer with sensitivity at 1-30Hz for Homestake will take quite some time, as modifications of electronic parts, mechanical parts, and materials must take place.

There are a couple of developing situations involving the electronics. One is deciding where to place capacitors that will be part of the new system for measuring how far the mass has been displaced. One idea of where to put these is:

> One capacitor on the section on the top part of the mass where the screw holes are not located and another above there. The same would be done on the bottom, with the capacitors in the same orientation.

Along with this, the current SS-1 Ranger that has been taken apart will be put back together. Right now it will use both the capacitors and the calibration coil; however, right now, there is no room for a capacitor to be placed on the bottom plate because the calibrated coil is glued down to the isolation plate, leaving no space for a capacitor [2]. To compensate this, the isolation plate's distance from the test mass will be expanded and other mechanical parts changed as needed to adjust for this addition [2,7]. This addition will be made by adding about a centimeter onto the wood colored cylinder at its bottom so the isolation plate will be further away from the mass when attached back to the wood colored isolation cylinder allowing room for the capacitors [2]. This compensation will be built into future seismometer as well when there is the calibration coil, which raises another point.

The calibration coil is glued onto the isolation plate. Glue weakens in strength over time causing "creeps" [8] where the coil will move ever so slightly [1] which could result in measurements being thrown off. This usually happens at low frequencies, but could potentially be a problem with frequencies around 1-30Hz [2]. If it is, alternatives to glue will have to be formulated. The more obvious alternative that would be used if necessary is using screws. Screws are good, but, as Jones and Richards say in *The design and some applications of sensitive capacitance micrometers*, if not put in properly, will cause significant "creeps" as well, allowing for material to shift with more ease [8]. If using this option, the screws must be screwed in slowly and carefully allowing for the screws to be put in at ease with less tension so the screws will not "break away" due to "creeps" [8]. A screw will "creep" over time no matter what, however, so selecting proper locations and using as few as possible is important [8]. If the glue is needed to be replaced, this issue with screws "creeping" may not be an issue; it is only a potential issue that may or may not arise if these are used instead of the glue. If it does become an issue, then where screws are placed all around the seismometer will need to be considered.

A more immediate issue to consider is the material used to design the seismometer. Materials will expand and lose stability over time, so using some materials is preferable over others. 70-30 brass that has been heat treated, modified to proper size, and then shielded from oxidation and water vapor absorption is one of the better materials for stability, and light alloys should be avoided [8]. For insulation, low expansion glasses are best [8], thus allowing for the insulation to not deform [8] and possibly throw off the measurements due to the seismometers structure changing ever so slightly. If it is found the SS-1 Ranger is made of some poor materials as opposed to more preferred ones, changes may be implemented so these preferred ones are used in the design, allowing for a more physically stable seismometer.

One other major factor to take into account is the limits the SS-1 gives itself (see Figure 10). Just like noise limits gravitational wave detectors, noise generated by the SS-1 limits how well it provides seismic data without a bunch of noise mixed in. The seismic noises that limit it greatly are amplifier voltage noise, amplifier current noise, Johnson-Nyquist noise, and the constant thermal suspension noise. These noises must be limited so seismic noise and thus NN can be studied at the target frequency of around 10Hz.

Limiting amplifier voltage and current noise is rather simple, a better amplifier just needs to be used [2]. Limiting the other seismic noises will be a bit more complicated, but the main idea is to use capacitors instead of coils. Johnson-Nyquist noise arises from the calibration coils. To avoid this, the calibration coils must be replaced and capacitors do this best, as these cause little noise [2]. Thermal suspension noise, along with other mechanical noises [2], has one or two possible sources. The most likely source is thermo mechanical noise from spring damping [2]. This would arise from the spring moving and damping in the spring's material causing noise [2]. Another possible source is eddy currents caused by magnets in the seismometer [2]. These eddy

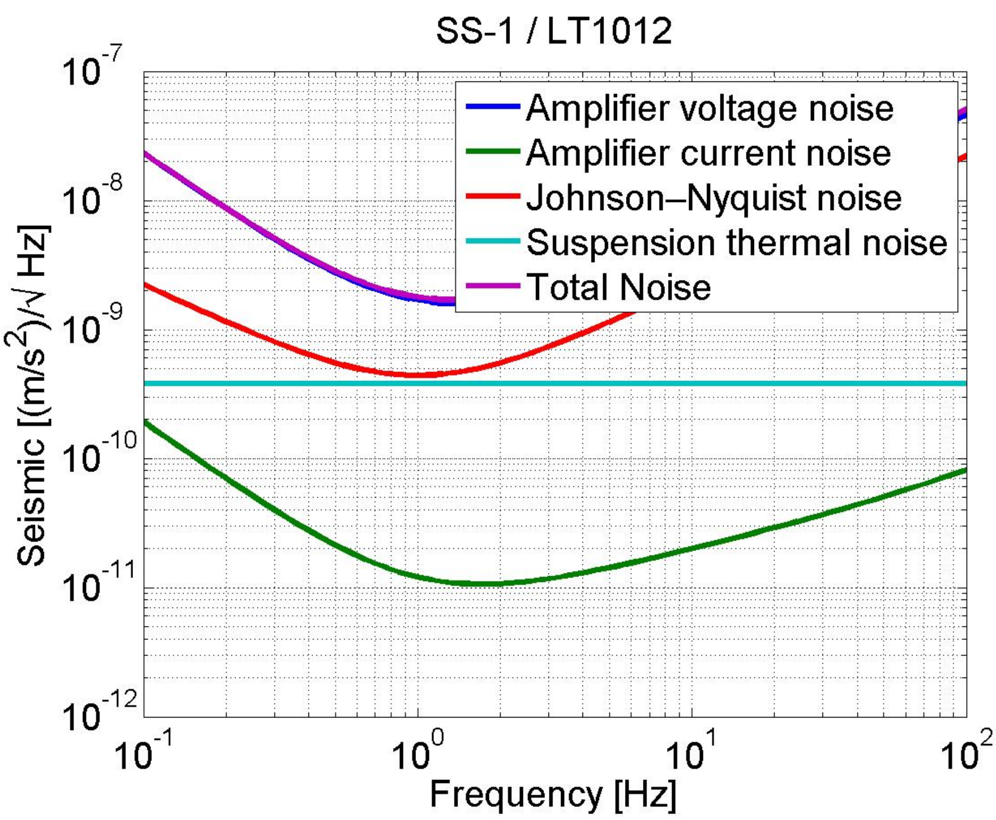

Figure 10: Seismic noise that limits the SS-1 Ranger. Focusing on the noise levels around 10Hz, changes must be made in the design of the seismometer to limit the effects this noise has one the effectiveness of data acquisition to study seismic and thus NN.

currents form when metal moves amongst magnets creating currents [2]. By Lenz's law, there is an induced current to counter the change in the magnetic field, which is this case is an eddy current. This eddy current creates noise. To get rid of it, removing coils will allow for less noise from eddy currents, but in the larger view of things magnets, if eddy currents are found to be a cause of thermal suspension noise, and other metal components need to be removed completely to minimize the noise the currents create a more substantial amount [2]. More will be known if these two sources cause thermal suspension noise when the SS-1 Ranger issued to study noise at the 10Hz level.

Current plans are to finish the modeling of the SS-1 Ranger and make measurements of the noise it picks up and compare it to the GS-13 and T240's noise measurements. Changes of the seismometer's design mechanically, electronically, and materially will be made as well and the changes will begin to be put in place to see how well the noise from the SS-1 is minimized.

For one final note, there is one more development at Homestake. Right now, a computer DAQ system is being used to make the data from the seismometers available [2,4]. The problem with this is that the humidity in the mine keeps destroying the computers [4]. It is thus desirable to acquire a data acquisition system that can hook into the DAQ system the computers are part of [2]. What will be used is being explored, but it will be preferable to have a system besides the computers if it is seen these continue to break with the new insulation box [4].

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