Modelling a mechanical antenna for a calibrator for interferometric gravitational wave detector using finite elements method

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Abstract: Interferometric gravitational wave detectors (IGWD) are a very complex detector, the need to lock the detector in a dark fringe condition besides the vibrations that affect the mirrors, creates the necessity of using active suspension systems. These active systems make the system reach the desired sensitivity but make the calibration of such detectors much more difficult. To solve this problem a calibrator is proposed, a resonant mass gravitational wave detector could be used to detect the same signal in a narrower band and use the measured amplitude to calibrate the IGWD, as resonant mass gravitational wave detectors are easily calibrated. This work aims to design the mechanical antenna of such a calibrator. The main difficulty is to design the calibrator is the frequencies required to make the detection. These massive detectors usually were made in frequencies close to 1 kHz and the frequency range to operate for better sensitivity is around 100 Hz. The antenna is modelled in finite elements method and a design of such an antenna is presented.

1. Introduction
Very soon after Albert Einstein developed his theory of General Relativity, there was many developments, one of such developments was the prediction of gravitational waves, as space time can be deformed and dictade how matter should move, if this medium is perturbed, such perturbations should propaged with the speed equal to the speed of light. So after one hundred years experiments to measure such speed are being proposed [1,2].
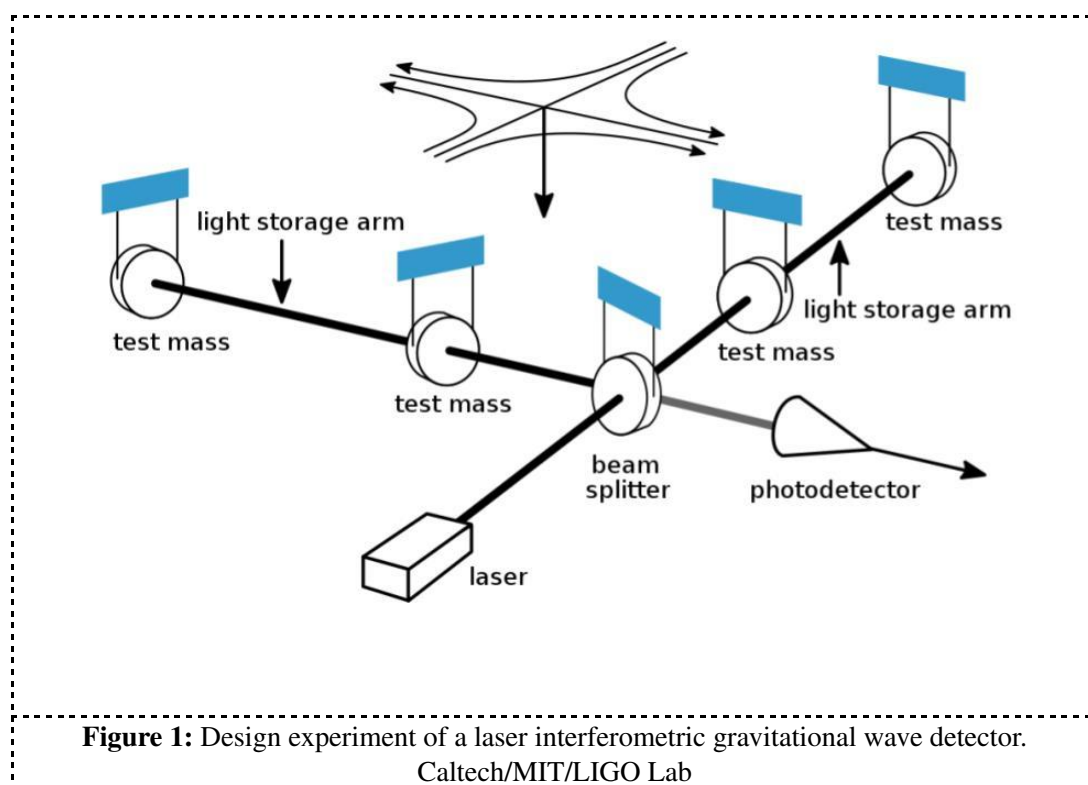
The authors are part of the GRAVITON Group which is a Brazilian research group dedicated to the study of gravity. In the search to understand, GRAVITON group members make many contributions to the field of gravitational waves; such efforts can be seen from reference [3] to [27] covering all sorts of aspects in gravitational wave detection.
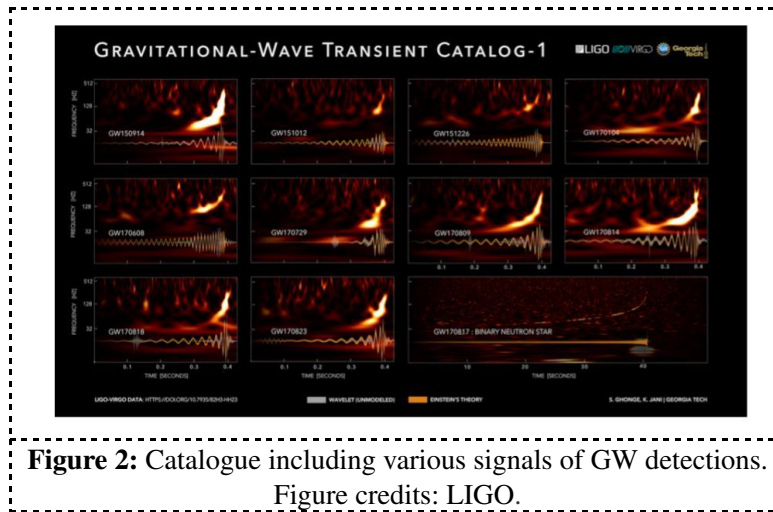
This expertise gave the author capability to develop a way to calibrate the big detectors that are claimed to have achieved the first detection of these waves.

2. The Laser Interferometric Gravitational Wave Detectors

Fig. 1 shows the experimental setup: it works as an interferometer, there is a laser source that emits a laser that is divided in two in a beam splitter then the laser enters in two optical cavities called arms, the laser is storage in both arms then they returns to the beam splitter and one fourth of the original laser power goes to the photodetector. The experiment is set in a dark fringe interference at the photodetector. When a gravitational wave arrives perpendicular to the apparatus it changes the length of the arms changing the interference pattern. The problem of the experiment arises when the vibration is taken into account. Vibration of any kind (seismic, thermal, etc) also changes the interference condition of the experiment. To avoid that, clever suspension systems were designed including active systems. The problem is that the active system could respond to the gravitational wave system as well making the calibration of the system quite difficult.

Figure 1: Design experiment of a laser interferometric gravitational wave detector. Caltech/MIT/LIGO Lab

Nevertheless the experiments are taking place and many transient signals were detected as can be seen in Fig. 2. The figure shows the signal in both domains: time and frequency, vertical for the frequency and horizontal for the time. In the figure can be observed that the highest intensity of the signal happens around the frequency of 125 Hz.

Figure 2: Catalogue including various signals of GW detections.
Figure credits: LIGO.

These were not the only gravitational wave detectors. There are the resonant mass gravitational wave detectors, they worked for many decades. They consist of a mass that, when the gravitational wave passes through it, vibrates if the system is in the same frequency of the gravitational wave (because of that the name resonant) [10]. There were many detectors working in coincidence around the world, as can be seen in Fig. 3.
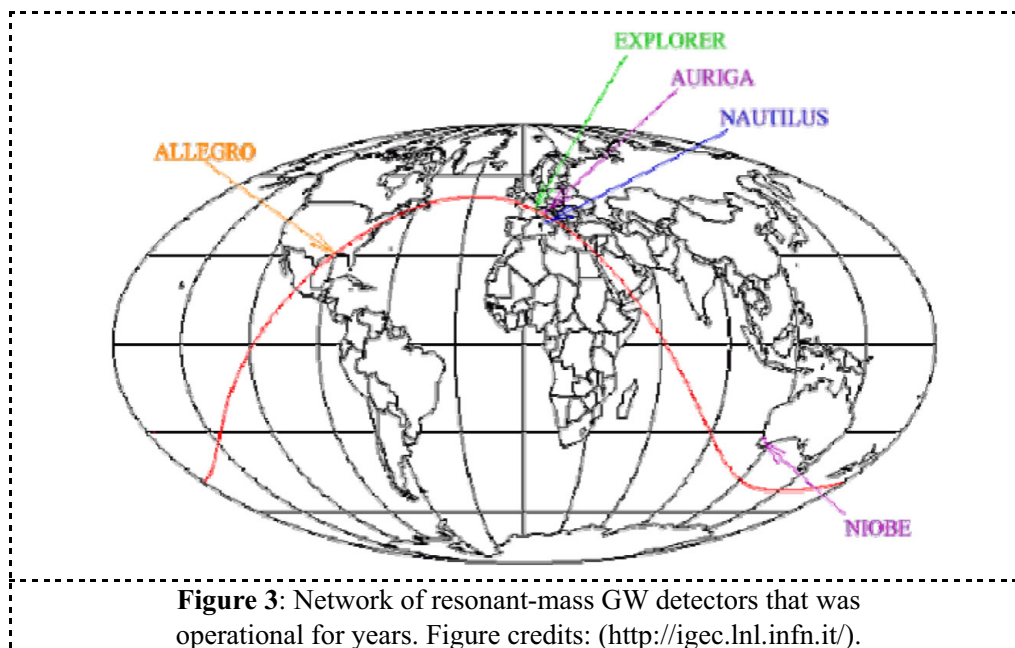
No gravitational wave was detected with this apparatus probably because the operational frequency was in a different range, they operated close to 1 kHz frequency, and as can be seen in Fig. 2 a good detection window will be close to 100 Hz. The frequency of 1 kHz came for historical reasons, the idea was to use a bar as a detector, and a bar that vibrates at 1 kHz is impractical to be constructed. Nevertheless thi kind of detectors are easily calibrated.

This work proposes a new kind of resonant mass antenna to build a gravitational wave detector and use the signal detected by such a detector to calibrate the laser interferometric gravitational wave detectors. This resonant mass is called the antenna of the detector.
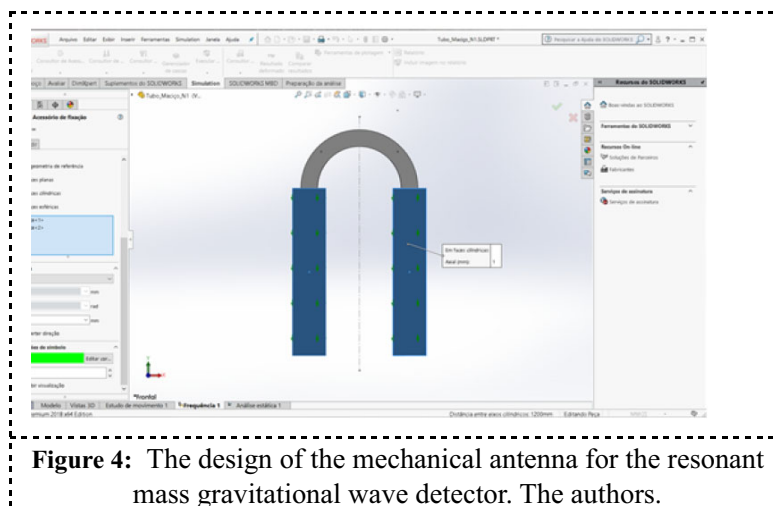
3. The mechanical antenna

In order to determine the resonant frequency of a new antenna, first the material should be chosen, as a main property for such a detector, the mechanical quality factor (Q_M) should be as high as possible. From the expertise of gravitational wave detection two materials appear as the best choice: pure niobium and sapphire. The problem with sapphire is to manufacture a big piece of it, as much as its high speed velocity, then the material chosen is niobium. The properties of niobium are as following: elasticity modulus of 98.6 GPa, ultimate tensile strength of 172 MPa, yield strength of 103.0 MPa, QM of 2 x 10^8, poisson ratio of 0,38 and hardness (nano identification) of 2.5GPa $Q_M = 2\ 10^8$.

To carry out the computer simulation, the commercial software platform SolidWorks was adopted as a tool, which uses the MEF to determine the important mechanical parameters of the project. With it, the CAD modeling (Computer Aided Design) was carried out using the parametric drawing tool integrated into the platform.

Figure 3: Network of resonant-mass GW detectors that was
operational for years. Figure credits: (http://igec.lnl.infn.it/).

Some designs were considered, the desired one should be one where the vibrational frequency could be changed for some parameters, it must be different from a bar where the only way to change axial vibrational frequency is to change the length. The chosen format is the one shown in Fig. 4, where a semicircle bar connects to masses, the frequency can be changed by modifications in the radios of the arc, its length, its diameter and the masses of the two sided bodies.

Figure 4: The design of the mechanical antenna for the resonant
mass gravitational wave detector. The authors.

4. The Modelling

The discretization of the antenna was made in the SolidWorks software. A uniform distribution of elements is enough for the application of the MEF and to discover the behavior of the structure, and this is facilitated thanks to the symmetry of the model. Then the antenna is simulated in the vibration normal frequencies package.

In Fig. 5, it is possible to observe the simulation result of the vibration normal frequency of the antenna for the mode of interesse. Such mode is the one where the two sided bodies vibrate in parallel ways, getting closer and farther but maintaining its alignment. Fig. 5 shows the movement in color scale, the bigger the movement the more the color changes to red, the smaller the movement the more the color changes to blue. The regions in blue are the good places to attach the mass to a suspension. For illustration the vibrational frequency in this simulation was close to 150 Hz.
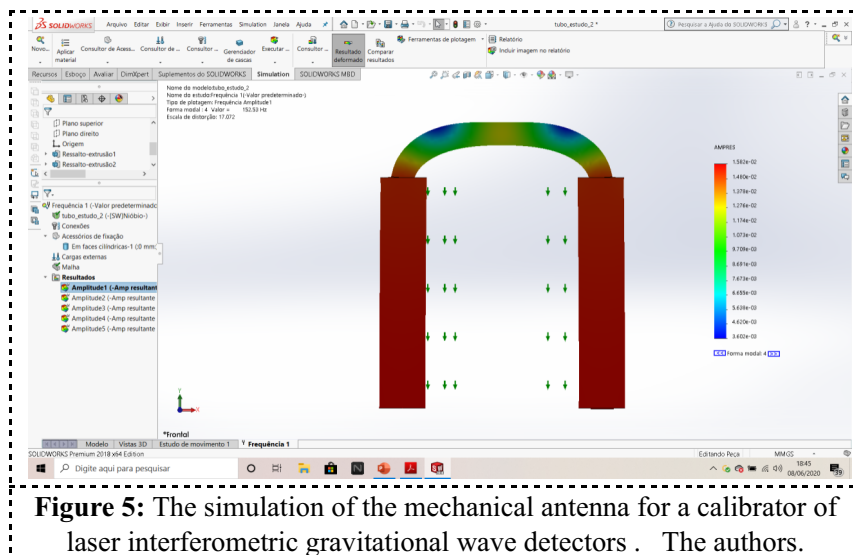

Figure 5: The simulation of the mechanical antenna for a calibrator of laser interferometric gravitational wave detectors .   The authors.

5. Conclusion

The shape chosen for the mechanical antenna of a laser gravitational wave detector calibrator is capable of reaching the desired frequency range of around 125 Hz.

The simulation also shows places where to connect the antenna with a suspension without decreasing the mechanical quality factor of the system, as the connection is in a place of almost no movement of the antenna.

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