Modelling a suspension for an experiment to measure the speed of gravity in short distances

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Abstract: An experiment to measure the speed of gravitational signals in short distances has been developed with the intention to study its behavior when a medium different from air is allocated between the emitter and the detection and check if the speed of the interaction changes. The experiment is composed of three sapphire bars that vibrates, and as they vibrate its creates a tidal gravitational wave signal that interacts with another sapphire bar, this bar is monitored by a very pure microwave signal and its amplitude and phase are measured and the gravity speed is calculated, all system is cooled to a temperature of 4.2 K to increase sensitivity and kept in high vacuum. The sapphire bar needs to be suspended to avoid seismic noise and other interference. This work models the sapphire bar with the suspension, a wire that suspends the bar by its center and has its performance calculated in a finite element modelling. The final result shows that the mechanical behavior of the sapphire bar is not affected by the suspension.

1. Introduction
Experiments to measure the speed of gravity are being planned [1,2], they are being developed by the GRAVITON Group, a Brazilian group dedicated to the study of gravity, which has gravitational waves as its main research area of investigation. GRAVITON group efforts toward the understanding of gravity can be summarized in references [3-27].
This knowledge developed in this field of GW developed in our group expertise to design the experiment to measure the speed of gravity over short distances.

2. The experiment artificial generates gravitational tidal signals and detected them
Fig. 1 shows the experimental setup: two PZTs make two sapphire bars to vibrate in phase at the same distance from a sapphire device that works as a detector. They need to be suspended and isolated from noise coming from outside the experiment. This is the main purpose of the suspension and will be described in more details in the next section. All the experiment operates at 4.2 K in high vacuum. Sapphire was the chosen material due to its physical properties: specific mass of 3.98 g.cm\(^{-3}\), sound velocity of 9.4 km.s\(^{-1}\), mechanical quality factor of 3\(\times\)10\(^9\), Young modulus of 431.80 GPa, shear modulus of 170 GPa, Poisson ratio of 0.27, tensile yield strength of 15.5 GPa and bulk modulus of 312.9 GPa.

![Figure 1: Design experiment with PZT vibrating in phase and generating a signal. From the authors.](image)

Some characteristic of the experiment:

- Oscillator phase noise: -165 dBc/Hz at 1 kHz offset;
  \[ M_{eff} = 1kg; \]
  \[ Q = 3 \times 10^9; \]
  \[ 10^{-4} \] (Vibration amplitude of the bars);
  0.2 m (Equivalent size of the bars);
  5.0 m (Distance between detector and emitter);
  Frequency bandwidth (BW): 2500 Hz;
  \[ f = 10^3 \text{ Hz} \]
3. The suspension

The following sections are the result of [28]. The suspension system adopted must be fixed to the sapphire transducer with the least possible friction, to avoid mechanical stress on the material. For this, fibers made of nylon or sapphire can be used, which will not significantly reduce the $Q_M$ of the system [29].

The sapphire transducer geometry will be in the form of a cylindrical bar as massive as possible, but other geometries can be studied, and in relation to sapphire manufacturing, some care must be taken so that the $Q_E$ and the $Q_M$ are the same, highest possible values: - the crystal's C axis orientation should be as parallel as possible to the cylinder's Z axis orientation, this provides the necessary electrical characteristics; - the sapphire piece cannot present bubbles in the manufacturing process, the bubbles reduce the speed of sound propagation in the material. - the length of the bar should be the largest available, this will enable the construction of the “Tide Gravitational Signal Generator”, directly influencing the dimensions of its project. Due to the availability of sapphire in the market, where its length has limitations of up to 500 mm in length, this is due to the technology for manufacturing this material, the gravitational signal generator must meet these limitations.

To study the behavior of the sapphire detector under the influence of a gravitational signal, the cylindrical shape was adopted for the detector, given the ease of finding sapphire pieces in this format in the specialized market and presenting a natural way that is it couples to the SGMP in addition to enabling a mass distribution that favors the fixation of the detector by means of a suspension through the central region of the piece. For this, the largest possible diameter in relation to its length was adopted, in order to satisfy the mass gain and availability of purchase of this material. The mass gain favors the distribution of natural modes with lower frequencies, since the excitation signal will come from a periodic tidal gravitational signal generator, the natural frequencies of interest occurring at the lowest possible values, enabling the construction of this equipment, since the rotation speed of the masses used may be lower. In order to reduce the friction between the detector and the material of the suspension as much as possible, it was decided to use a wire to suspend the part, in order to maintain the smallest possible contact area between it and the surface of the detector, thus reducing friction in the region of contact between the two. To carry out the computer simulation, the commercial software platform ANSYS® 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.

Some sketches of the model built in ANSYS® will be described below. In Fig. 2 it is possible to observe the profile of the detection system, leaving exposed the piece of sapphire supported on the niobium wire that composes the suspension.

The wire that makes up the suspension has a volume given by the revolution of an area of circumference of diameter $D$ on the curved line of the profile. After some construction operations on the profiles, the solid represented in Fig. 2 is obtained.

The contact between the suspension surface and the sapphire cylinder surface is made through a tangential contact to the cylinder surface, and to model the finite elements in this region in ANSYS® there is an operation called "Imprint Faces" that must be performed, which allows establishing the contact area between the parts that make up the detector through finite elements that allow the configuration of the coefficient of friction of the contact zone between the suspension and the sapphire cylinder, this operation marks the cylinder's contact area when there is no significant mechanical interaction, for example, when gravity is zero, this is a prerequisite for the software to be able to calculate transients during the simulation process and the deformation suffered by solids after the interaction of forces.
For the simulation performed in this work, all the simulation parameters are considered under the hypothesis of an invariant temperature at 4 K, thus the parameters that vary as a function of temperature will not be considered as their variations, but rather as their constant value at this work point. It is expected that with a cooling around this temperature, the electrical and mechanical Q ($Q_E$ and $Q_M$) of the materials converged to the highest possible values, in addition to reducing the thermal noise in the structure.

For the contact analysis of the suspension with the detector, a mechanical parameter is needed, the coefficient of dynamic friction between the Niobium suspension and the Sapphire bar. This parameter is obtained through the essay available in “Wear Particles: From the Cradle to the Grave, 1st Edition, Elsevier Science, Edited by D. Dowson, G. Dalmaz, T.H.C. Childs, C.M. Taylor, M. Godet, 1992”. In this book, a test is performed by testing a spherical sapphire piece and another cylindrical one under friction in another Niobium piece, the test parameters are mentioned that include displacements with a velocity of 24 mms$^{-1}$, normal load to the surface of 5 N, relative humidity between 40% and 60% and 1000 test cycles on the tribometer. In this test, care was taken to avoid plastic deformation on the contact surface. The graph of such an experiment can be seen in Fig. 3.
4. The Modelling
The discretization in the region around the friction area must contain a greater number of finite elements to better describe the contact behavior between solids and in other regions 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 and the type of mechanical load used in the analysis. The contact regions are defined with specific finite elements which receive as a parameter the coefficient of friction between the materials involved. In Fig. 3, it is possible to observe the region of the suspension that is in contact with the sapphire cylinder. The Imprint Faces operation performed during 3D solid modeling marks this region with an edge that can be selected for parameter adjustment.

The contact occurs between the finite elements of the line obtained through an operation called Imprint Faces performed during the construction of the geometry of the entire structure, this operation places a line on each contact face of the solids (detector and suspension) that marks the point of tangent contact, this line is considered an edge. These edges can be selected as parameters for configuring the contact. Contact configuration must be performed in conjunction with the fabric configuration. ANSYS® provides automatic contact configurations, but for this case, where the contact type is tangential, around two edges and there is friction between the faces, we adopt the manual configuration that allows establishing the friction contact parameters. ANSYS® has several types of contact configuration, from the Bonded type, which considers that the parts involved are always joined and no type of relative displacement occurs, to the Frictionless configuration type, which allows the assignment of a null coefficient of friction between the contact zones, so the parts can slide freely even with a force normal to the contact surface. The Frictional contact offered by the software allows establishing the coefficient of friction between the niobium suspension and the sapphire detector. Adjustment of material parameters in mechanical simulation. The friction coefficient presented in this section, according to the data obtained in Figure 3 is around 0.36. The edges on the cylinder face and suspension are selected as parameters for the contact configuration. The edge on the face of the cylinder will be the Target element and the edge on the face of the suspension that is in contact with the cylinder will be the Contact element.

5. Results
The static simulation results aim to analyze whether the suspension is strong enough to support the weight of the sapphire piece and if the sapphire piece supports the friction of the niobium wire under its surface, these results are obtained through the ANSYS solution tools ® and are presented in the form of graphics and color gradients on the solid, or through the presentation of vectors that indicate the direction of deformations or efforts. The first solution obtained is on the deformation of the suspension wire. This information is presented using vectors. Visualizing the vectors displays the expected displacement when the sapphire piece is placed over the niobium suspension wire. Vectors indicate the trend of displacements caused by the weight of the sapphire piece.

The evolution over time of the suspension deformations can be seen in Fig. 4, it can be seen the distension suffered by the suspension wire due to the weight of the cylinder, the circular shape marks the position of the cylinder.

It is possible to observe on a larger scale the deformation of the detector due to its own weight. The detector ends cause momentum in the central region of the body. The ends work like two levers. This deformation is very small, but it is still possible to visualize it by enlarging the visualization scale.

The piece will resonate at the approximate frequency of 27191 Hz. The vibration mode compression semi-cycle is shown in Fig. 5. There is a corresponding cycle of expansion. At moment (A) the part is at zero deformation and the cycle evolves to contraction at moments (B), (C) and (D).
6. Conclusion
A Sapphire Transducer for Gravitational Interaction Velocity Measurement was designed, applying the Finite Element Method and the Frequency Domain Finite Difference Method to analyze the mechanical and electrical frequency response. The analysis of the detector's natural vibration modes makes it possible to establish at which frequency the vibration mode that best couples periodic tidal gravitational signals occurs. The axial vibrate mode is the best excitation study mode for a cylindrical sapphire bar, as the nature of periodic tidal gravitational signals causes a deformation in the length of the detector by compressing and extending it, causing it to oscillate. The application of the axial vibrate mode, in addition to allowing the part to vibrate at the resonant frequency, allows an amplification of the mechanical excitation signal to take place given the nature of the mechanical resonance, this allows mechanical amplifiers to not need to be used, as at the frequency of resonance the sapphire part of the detector undergoes large deformations that are used to carry out the parametric transduction.
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