A Method to Design Mechanical Transducers for Resonant Mass Gravitational Wave Detectors

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Abstract

In this work a method to design two mechanical modes transducers for spherical resonant mass gravitational wave detectors is presented. Applied for SCHENBERG detector that uses microwave multiparametric sensors. The detector has 17 mechanical modes and more 6 electromagnetic modes for the microwave cavities. Here these aspects of the mechanical design that should allow amplification in amplitude around 10000 times. For this to be possible, these transducers, when placed on the spherical surface of the detector, must meet conditions that involve: size limitations, can be manufactured with a high mechanical and electrical Q, have an effective mass ratio between their modes to provide the intended amplification and compose a resonant system that has characteristics necessary for the detection of gravitational waves (GW). To meet this last aspect, the transducers must form a resonant system with the sphere around the quadrupole frequencies of the sphere. This work describes how these transducers were designed to be able to meet all these conditions. In this project, the use of simulations using the finite element method (FEM) was essential.

Introduction

When an GW passes through the detector's spherical resonant mass, it vibrates and the movement produced on its surface, which is monitored by motion sensors called transducers, transform mechanical oscillation into an electrical signal. The Mario detector Schenberg will have six transducers, located on the surface of a $65cm$ diameter sphere, as if they were in the center of 6 pentagons located in the upper half of a dodecahedron circumscribed to the sphere.

By analyzing the electronic signal of these sensors, the intensity and direction of the GW is coming. The Schenberg will have a resonant frequency around $3.2kHz$ with a bandwidth close to $200Hz$.

Among the types of existing transducers, the Brazilian group decided to use microwave multiparametric transducers as motion sensors. In the superconducting cavity of these transducers, a resonant monochromatic microwave signal will be injected. This kind of transducer allows the use of various formats.

An mechanical transducer is a small mechanical oscillator that couples the vibration modes of the sphere with the of the sensor, selecting the frequency of interest, and doing the mechanical amplification of the sphere vibration. This amplification varies with the square root of the ratio between the effective mass of the sphere and effective mass of the oscillator or resonator.

Main Objectives

The main objectives in a good transducer project are:

1. ensure the coupling of the ball's vibration modes with the sensors, selecting the frequency of interest,
2. obtain the greatest possible mechanical amplification of the movement, due to the vibration of the sphere, of the region where it is connected.

Methodology

The resonant sphere, to be used as an antenna, requires the addition of the transducers and a support system, which alter their mass, geometry and symmetries.

Therefore, the first step of the work was to evaluate the effect of these changes made on the quadrupole modes of the resonant mass used, conceived from a massive sphere. Simulations were made with a program that uses MEF (the SolidWorks program was used).

The following sphere configurations were analyzed:

- the massive sphere,
- the sphere with the transducer connection holes and
- the sphere with the transducers connection holes and the suspension hole, which has the conical part in its central region, which is connected to the lower suspension rod.

The analysis of the modes obtained through the simulations shows that, when introducing the holes for connecting the transducers in the sphere, there was a small increase in the frequency of the quadrupole modes, an increase that can be attributed to the reduction of the sphere mass.

The analysis of the modes obtained through simulation after introducing the holes to house the suspension and the transducers, indicated an increase in the average frequency when compared to that of the massive sphere. This increase is possibly associated with the location of the region from which the sphere's mass was removed. The band and standard deviation increased, characterizing a break in symmetry and that the frequencies of these modes can no longer be considered degenerate.

In the next phase, the idea was, basically, to build the final model, which we want to optimize, by superimposing simpler models. Among the physical criteria used to assess the model and assess the degree of optimization were adopted:

- the simple verification of the vibration coupling (resonance) between the sphere and the first transducer mode.
- the band obtained between normal modes coupled within the same modal group (doublets and quintuplets, for example).
- for the second mode configuration (membrane), a satisfactory or functional model would be one in which the modes in phase and counter phase , of the membrane with the added extension, had a band compatible with the band of the antenna.
- to choose the mechanical transducer format, when separately simulating each candidate transducer, an attempt was made to obtain a calibration so that its two interest modes were around $3200\ Hz$. The two modes sought corresponded to the phase movement of the coupled modes of the first and second masses and, in the other mode, in phase opposition.
- verify that the physical masses involved were compatible with the effective masses in each mode, which are necessary masses to achieve the desired amplifications. In the case of SCHENBERG the effective mass of each quadrupolar mode of the sphere is $287\ kg$ and the effective masses of each mode of the mechanical transducer would be $30\ g$ and $30\ mg$.
- from the analysis of two types of membranes, check the compatibility with the required amplification. The thickness of the membrane and the dimensions of the spring were changed until it was achieved that the band frequencies were as smaller as possible.
- simulations of the mechanical transducers connected to the sphere. In this step, due to the delay in simulations with six transducers connected to the sphere, initially only one transducer connected to or separated from the sphere was used to simplify the model configurations. It is important to note that efficient mesh knitting is difficult when there is a large dimensional variation between the parts of the model that are connected, as occurs in the connection of the transducer with the sphere.
- simulation of six mechanical transducers on the sphere, starting with the configuration of the best result obtained so far.
- Finally, the mass and spring of the first way still had to be changed to obtain the calibration between the bands.

Results

In the first stage of the work, it was obtained from simulations using the FEM that:

- the effect, in the resonate modes, when introducing the connecting holes of the transducers on the solid sphere was a small increase in the frequency of the quadrupole modes, an increase that can be attributed to the reduction of the resonant mass.
- the effect, in the resonate modes, when introducing the central hole in the sphere with the transducer connecting holes already, was an increase in the average frequency of the order of $24.4\ Hz$, when compared to that of the massive sphere. This increase is possibly associated with the location of the region from which the sphere's mass was removed. The band and standard deviation increased by $37.22\ Hz$ and $15.72\ \ Hz$, respectively, characterizing a break in symmetry. Therefore, the frequencies of these modes can no longer be considered degenerate.
- the results obtained in the analysis of the second transducer mode, which corresponds to a membrane of constant thickness, have been compared to known and widespread experimental results. These results served to validate the settings used for the mesh in the simulation model (FEM) for this transducer element.
- it was possible to choose a type of transducer that allowed to change the spring effect and the physical mass (and the effective mass) in its first mode, by changing only two parameters.
- The efficient mesh knitting is difficult when there is a great dimensional variation between the connected parts of a model, as it happens when connecting the transducer to the sphere.
- in one of the two mode mechanical transducers, which had been analyzed with the sphere, one of its modes was obtained coupled with the sphere. A new calibration of this transducer was made, made separately and seeking to approximate its main frequencies. A configuration was obtained that was tested initially with the ball without a central hole and then with a ball with a central hole. Again, a coupling of the main modes was achieved and, still, these frequencies remained close.

The two figures below show graphs that summarize the evolution of the results achieved. In the first, graphs are displayed for 6 transducers in two modes connected to the sphere without the central hole. The second, in two graphs, presents these results for a sphere with a central hole. It is possible to notice in the two figures that the modes assumed an increasingly symmetrical and less spread distribution and the total band decreased. The red bars indicate the frequencies corresponding to the singlets.

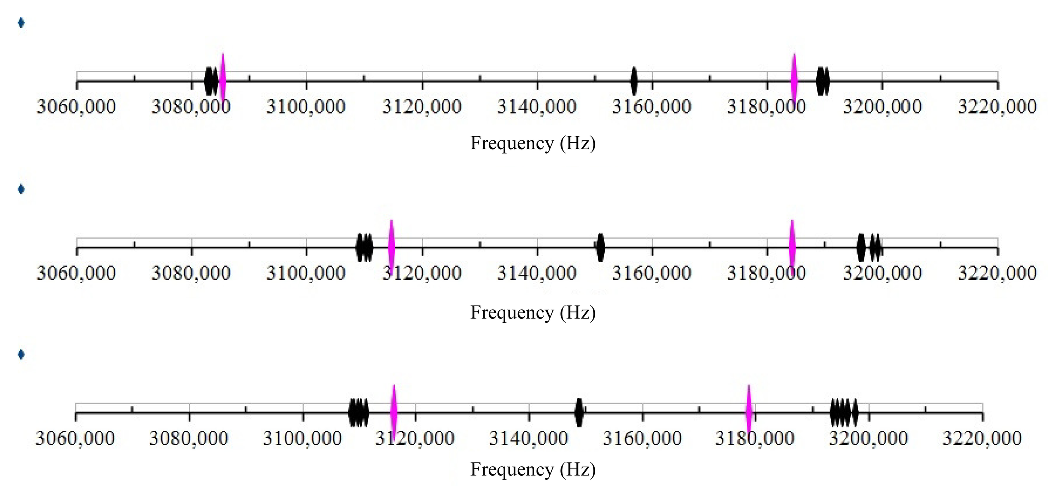

Figure 1: In the three graphs of the figure, the 17 normal modes (the quintuplets appear overlapping) obtained by simulation (FEM) for 6 mechanical transducers in two modes connected to the sphere **without the central hole** are displayed.

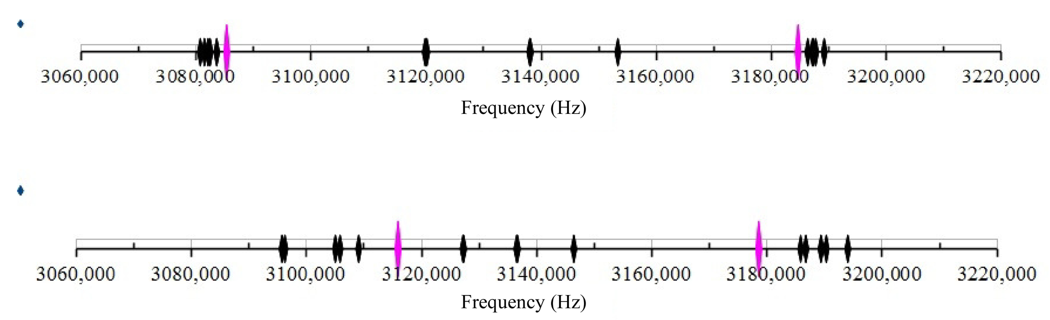

Figure 2: In the two graphs of the figure, the 17 normal modes (the quintuplets appear overlapping) obtained by simulation (FEM) for 6 mechanical transducers in two modes connected to the sphere **with the central hole** are shown.

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