Studying a new shape for mechanical impedance matchers in Mario Schenberg transducers

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"Mario Schenberg" is a spherical resonant-mass gravitational wave (GW) detector that is expected to be part of a GW detection array of two detectors. Another one is been built in The Netherlands. Their resonant frequencies will be around 3 kHz with a bandwidth of about 200 Hz. This range of frequencies is new in a field where the typical frequencies lay below 1 kHz, making the transducer development much more complex. Some studies indicated that the use of low mass mechanical resonators (used for impedance matching to the parametric transducer, in a cold damping regime) allows the detector to reach the standard quantum limit. In this work we describe the study of a new shape for the impedance matching resonator used to obtain a better coupling between the sphere and the transducers and a better use of the space inside the experimental chamber.

1. Introduction

"Mario Schenberg" [1] is a spherical resonant-mass gravitational wave detector weighting 1.15 ton, being built at the Department of Physics of Materials and Mechanics at the University of Sao Paulo. The sphere, with 65 cm in diameter, is made of a copper-aluminum alloy [2] with 94% Cu and 6% Al. The distribution of motion sensors in the surface of the sphere will be based on the work by Merkowitz and Johnson [3], confirmed by Magalhaes et al. [4]. Motion sensors are devices that monitor the motion of the sphere surface. The detector will have six motion sensors, also called transducers, arranged on the sphere surface in a half-dodecahedron distribution; the sensors will be located as if in the center of the 6 connected pentagons in a dodecahedron surface. By analyzing the signal of these sensors the intensity and the direction of the incoming gravitation wave can be obtained [5]. A similar detector is been built in The Netherlands, called "MiniGrail" [6].

Transducers are used to measure the vibration of the sphere surface. The Brazilian group has decided to use as such motion sensors microwave parametric transducers, as the ones used in the GW resonant-mass detector NIOBE by the Australian group [7], where a superconducting cavity is pumped with monochromatic resonant microwaves. When the size of the cavity changes due to the vibration (one of the cavity walls is connected to the sphere by the mechanical impedance matcher), it creates two side bands in the microwave signal that leaves the cavity, the amplitude of the side band being proportional to the sphere vibration. A complete noise model for this detector can be found in [8].

The transducer mechanical impedance matcher is a small mechanical oscillator (resonator, as it has the same frequency of the sphere) that couples the sphere vibration modes to the transducer, making also a mechanical amplification of the sphere vibration. This amplification varies with the square root of the mass ratio of the effective mass of the sphere and the effective mass of the small mechanical oscillator (resonator).

2. The new shape for the impedance matcher

This kind of transducer allows the use of other shapes for the impedance matcher. A 3-dimensional view of the one used in this work can be seen in Figure 1, where one end of the cylinder will be connected to the sphere. The other end will be connected to a beam that will vibrate with the resonant frequency of the sphere quadrupole modes and an open microwave cavity (as the one used in [6]) will be mounted in the end of the beam, which has length around 10 cm. A draw of this part can be seen in Figure 2. We studied this impedance matcher shape trying to optimize the space inside the experimental chamber, keeping in mind that it is necessary to measure the sphere vibrations close to the sphere equator. If this kind of mechanical impedance matcher shows itself useful, it can be mounted close to the sphere equator.
with the beam pointing to the center of the experimental chamber, allowing the use of a bigger sphere in the same experimental space. The study was performed as follows.

3. The modeling

First we started by modeling the sphere with finite element modeling to obtain a sphere made of copper-aluminum that had the quadrupole modes at 3200 Hz. This was made for testing the modeling. The sphere torsional modes were found around 2990 Hz and the quadrupole modes were located around 3180 Hz. Then the impedance matcher was added to the sphere, then a first difficulty appeared, using the available dimensions inside the experimental chamber and the desired frequency, the size of the impedance matcher is small, this makes the detection band quite narrow (around 40 Hz), no way was found to improve this bandwidth.

Then we tried to model the impedance matcher with exactly the same frequency, but the finite element-modeling program could not handle the calculations with this exact frequency. It only calculated the modes with a frequency slight higher or lower. We chose, at this point, the lower one. We could see the impedance matcher modes coupled to the sphere quadrupole (at the frequencies: 3155, 3183.4, 3183.5, 3185.2, 3185.9 and 3194.2 Hz) but the impedance matcher also coupled to torsional modes at 2991.5 Hz (see Figure 3 for a general view of the animation made by the finite element program). Figure 4 shows snapshots of the animation of this vibration mode, where the vibration of the beam can be easily seen; the torsional motion can also be seen in the mesh that looks distorted from one snapshot to another.

This coupling is undesirable. It creates another mode with signal in a different frequency besides dissipating energy from the detection frequency band, but as the detection band (40 Hz) is small compared to the distance between the torsional and quadrupole modes (165 Hz), the coupling should be small. This situation improved completely when the simulation was made with the impedance matcher frequency slight higher from the resonant one. In this case six modes where found which are clearly combinations of the impedance matcher mode and the sphere quadrupole mode, with the following frequencies: 3167.5, 3183.3, 3182.5, 3185.3, 3185.9 and 3206.4. The amplification of movement in the torsional mode is also much smaller.

4. Conclusion

The design of this kind of transducer mechanical impedance matcher seems to be very delicate. A small change in the vibration frequency may change how this impedance matcher couples to the quadrupole and torsional modes. It can be designed to have better modes. It’s worth to remember that when the transducer is pumped with microwave signal it will move the frequency down, this could make this kind of impedance matcher unsuitable for use in this kind of detector. The next step is to model six of these impedance matchers in a half-dodecahedron distribution and analyze the modes, including some in higher frequencies.

Figure 1: Two views of the impedance matcher. The view on the left shows mainly the beam that vibrates and the right one shows mainly the cylinder that connects the part to the sphere.
Figure 2: The drawing of the mechanical impedance matcher with its dimensions in mm.

Figure 3: A view of one of the pictures used in the animation of the torsional modes at 2991.5 Hz.
Figure 4: Set of pictures from the animation highest torsional mode at 2991.5 Hz.

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