Advances in the project of the gravitational signal generator device to measure the speed of gravity

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Abstract. This work shows the latest improvements in the geometry of the quadrupole mass of a gravitational signal generator device, which should be used in an experiment to measure the speed of gravity. This device must generate a tidal gravitational signal with a frequency of 3200 Hz. The gravitational wave detector Mario Schenberg, developed in Brazil, is the first option as the detector of the signal. The previous steps of the project are briefly discussed, and the new FEM (finite element modeling) simulation for the quadrupole mass is shown. An analysis of the mechanical stresses produced at high speed rotation is presented. The new FEM simulation yields a favorable geometry for the inclusion of the magnetic suspension of the quadrupole mass. The results indicate the feasibility for the continuation of the project and subsequent construction of the real device.

1. Introduction

The detection of gravitational waves through the LIGO experiment [1] has opened the possibility of determining the speed of gravity, especially after the simultaneous measurement of gravitational waves and electromagnetic waves from the same astrophysical source [2]. Nevertheless, the speed of gravity is still a physical quantity very difficult to measure. The purpose of this project is to measure the speed of gravity by emitting a Newtonian gravitational signal from a device on Earth, and then detecting it by a second device. In this article, the first steps of the project are discussed.

The purpose of this work is to show the status of the project of a periodic (tidal) gravitational signal generating device, which should rotate a non-cylindrically symmetrical mass (quadrupole mass) at a frequency of 1,600 Hz (96,000 rpm). It is intended that the generated signal be detected by the gravitational wave detector Mario Schenberg [3–6].

Mario Schenberg is a spherical detector of resonant mass type; its spherical antenna has 1.15 tons, 65 cm in diameter, consists of a copper-aluminum alloy with 94% Cu and 6% Al, and has a mechanical quality factor $\sim 10^6$. The detector is projected to operate with at least six electromechanical transducers to monitor the vibrations of the antenna when interacting with the gravitational wave. The project of Mario Schenberg has been developed by the Brazilian research group Graviton [7]. The Brazilian efforts on this field are summarized in Refs. [3–6,8–11,13–21].

In Section 2, the previous stages of the project of the gravitational signal device are briefly discussed. In Section 3, the recent results obtained with the use of the finite element modeling...
2. Previous stages of the project
The previous stages of this project are described in more detail in Refs. [11,12]. In this section, a brief description of the previous stages is made. A schematic illustration of the gravitational signal generator device is shown in Figure 1.

The first stage of the project was the development of a simplified modeling of the emitter-detector system, which is described in detail in our previous work [11]. The simplified modeling shows the following relation for the gravitational signal amplitude $h$:

$$h \propto \frac{a^2 M Q}{\omega_0^2 r^5},$$

where $Q$ is the mechanical quality factor of the detector, $\omega_0$ is the resonance angular frequency of the detector, $r$ is the emitter-detector distance, $M$ is the mass of one of the symmetrical halves of the quadrupole mass, and $a$ is the distance of the c.m. of this symmetrical half from the rotation axis. Therefore, the product $Ma^2$ is the quantity to be optimized in the emitter.

The optimization process of the quadrupole mass started from the geometry shown in Figure 2. The optimization calculations are described in detail in Ref. [11]. A rotational frequency $f = 1,600$ Hz is considered, which produces a gravitational signal compatible with the central resonant frequency of the detector Mario Schenberg (3,200 Hz). The optimized dimensions for the quadrupole mass are given in Table 1.

A second configuration was proposed for the quadrupole mass aiming to reduce the von Mises stress in its central region, however, avoiding very significant changes on the initial geometry of Figure 2 (see details in Ref. [12]). The stress analysis in the quadrupole mass was performed through the software SOLIDWORKS [22]. The second proposed geometry is shown in Figure 3, indicating that the von Mises stress in the central region is satisfactory.

3. New results obtained with FEM
A new geometric configuration was proposed for the quadrupole mass, as seen in Figure 4. The goal of the new FEM simulation is to find a geometry with lateral holes for the composition of
Table 1. Optimized dimensions for the quadrupole mass of the gravitational signal device and the corresponding product $Ma^2$. $r_{\text{hole}}$ is the fixed value for the central hole radius.

|   | $d$ (cm) | $l$ (cm) | $q$ (cm) | $p$ (cm) | $s$ (cm) | $r_{\text{hole}}$ (cm) | $Ma^2$ (kg · cm$^2$) |
|---|---|---|---|---|---|---|---|
|   | 2.85 | 2.4 | 0.4 | 4.71 | 20.73 | 1.25 | 97.35 |

Figure 2. The first proposed geometry for the quadrupole mass system: (a) the cross-sectional view and (b) the perspective view. Component materials: carbon fiber → green and yellow; Maraging steel → blue; carbon fiber laminate → orange.

Figure 3. Representation of the quadrupole mass in its second geometry – section in the $yz$ plane. The von Mises stress color scale is shown (given in Pa). A rotation of 96,000 rpm is considered.
Table 2. Properties of the materials used in the composition of the quadrupole mass.

| Material                        | Density ($g/cm^3$) | Young’s modulus (GPa) | Ultimate strength (MPa) | Yield strength (MPa) |
|---------------------------------|--------------------|-----------------------|-------------------------|---------------------|
| Maraging Steel 2800             | 2800               | 8.00                  | 210                     | 2693                |
| (a)                             |                    |                       |                         |                     |
| Carbon fiber (thread) + epoxy composite | 1.634             | 190.3                 | 3530                    | ——                  |
| (b)                             |                    |                       |                         |                     |
| Carbon fiber (laminate) + epoxy composite | 1.55              | 138                   | 1550                    | ——                  |
| (c)                             |                    |                       |                         |                     |
| (d)                             |                    |                       |                         |                     |
| (e)                             |                    |                       |                         |                     |

a) Obtained from Ref. [23]
b) Obtained from the densities of carbon fiber [24, 25] and epoxy [26]
c) Obtained from the Young’s moduli of carbon fiber [24] and epoxy [26]
d) Ref. [27]
e) Obtained from Ref. [28]

the magnetic suspension of the quadrupole mass, as well as to reduce the mechanical stresses at critical points. Such holes should accommodate magnets which will compose part of the magnetic bearing system of the gravitational signal device. The lateral holes are 35 mm in diameter and 35 mm deep. Other geometric features were maintained relative to the configuration of Ref. [12].

The FEM simulation resulted in the von Mises stress distribution of Figure 5. The maximum von Mises stress observed is 2.553 GPa, while the configuration without lateral holes of Figure 3 has a maximum von Mises stress of 2.575 GPa. Therefore, a small reduction of the maximum stress was achieved. In addition, this result is gratifying since the maximum stress is below the yield strength of Maraging Steel 2800 (see Table 2). The von Mises stress values in the carbon fiber components are quite satisfactory, i.e., well below the ultimate tensile strength values of Table 2.

4. Conclusions and prospects
In conclusion, the FEM simulation performed for the new geometry of the quadrupole mass at 96,000 rpm allowed a small reduction in the von Mises stress in comparison with the previous geometry of Ref. [12] and, additionally, the inclusion of the lateral holes for mounting the magnetic bearing system, which are required for the suspension of the quadrupole mass. Therefore, the new configuration is closer to an ideal condition for the construction of a real device.

The configuration of the quadrupole mass can still be modified to reduce the maximum von Mises stress. This can be done by changes in its geometry or the choice of carbon fibers with better mechanical properties. Thus, we intend to present the evolution of this project in future publications.

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Figure 4. New proposed configuration for the quadrupolar mass after the FEM simulations. Dimensions given in mm.

Figure 5. Representation of the quadrupole mass in its latter geometry – section in the $yz$ plane. The von Mises stress color scale is shown (given in Pa). A rotation of 96,000 rpm is considered.
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