Brazilian Journal of Physics
ISSN: 0103-9733
luizno.bjp@gmail.com
Sociedade Brasileira de Física
Brasil

da Silva Bortoli, Fabio; Frajuca, Carlos; Turano de Sousa, Sergio; de Waard, Arlette;
Simao Magalhaes, Nadja

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Brazilian Journal of Physics, vol. 46, núm. 3, 2016, pp. 308-315
Sociedade Brasileira de Física
Sâo Paulo, Brasil

Braz J Phys (2016) 46:308–315
DOI 10.1007/s13538-016-0413-8

GENERAL AND APPLIED PHYSICS

On the Massive Antenna Suspension System in the Brazilian Gravitational Wave Detector SCHENBERG

Fabio da Silva Bortoli[1] · Carlos Frajuca[1] · Sergio Turano de Sousa[2] · Arlette de Waard[3] · Nadja Simao Magalhaes[4] · Odylio Denys de Aguiar[5]

Received: 31 October 2015 / Published online: 23 March 2016

Abstract SCHENBERG is a resonant-mass gravitational wave detector built in Brazil. Its spherical antenna, weighting 1.15 t, is connected to the outside world by a suspension system whose main function is to attenuate the external seismic noise. In this work, we report how the system was modeled using finite elements method. The model was validated on experimental data. The simulation showed that the attenuation obtained is of the order of 260 dB, which is sufficient for decreasing the seismic noise below the level of the thermal noise of the detector operating at 50 mK.

Keywords Gravitational wave detector · Gravitational wave suspension · SCHENBERG suspension

1 Introduction

SCHENBERG is a resonant-mass gravitational wave (GW) detector [1, 2] built in Brazil. Its spherical antenna, with 65 cm in diameter and weighting 1.15 metric ton, is made of a copper-aluminum alloy [3] with 94 % Cu and 6 % Al. The detector is projected to operate with at least six electromechanical transducers [4, 5], arranged in a half-dodecahedron distribution on the sphere surface, where the sensors are located at the center of the six connected pentagons in a dodecahedron surface, following the studies by Merkowitz and Johnson [6, 7] confirmed by Magalhaes and collaborators [8]. The detector's central resonant frequency is around 3200 Hz.

By analyzing the signal of such sensors, the amplitudes and the direction of the incoming gravitation wave can in principle be obtained [9, 10]. The Schenberg group has decided to use microwave parametric transducers as motion sensors, like the one used in the Australian GW detector NIOBÈ [11]. In this kind of transducer, a superconducting cavity is pumped with monochromatic resonant microwaves and when the size of the cavity changes due to vibration (one of the cavity walls is connected to the sphere by a mechanical impedance matcher) two side bands are created in the microwave signal that leaves the cavity. The amplitude of the side band is proportional to the amplitude of the sphere vibration. Such transducer was tested in Schenberg [12]. A history of decisions taken relatively to detector design can be found in reference [13].

External mechanical noise on the antenna, either seismic or not seismic, can jeopardize the required sensitivity of these transducers. Schenberg uses a suspension that aims at reducing these noises down to a level that will not surpass the very low thermal noise that remains after cooling the detector down to cryogenic temperatures. In this work, drawing on the experience gained from the knowledge of the transducers, the vibrational behavior of the entire suspension was investigated using finite element modeling and the results were validated using experimental data. This allowed

✉ Fabio da Silva Bortoli
bortoli@ifsp.edu.br

1 Departamento de Mecanica, Sao Paulo Federal Institute, Sao Paulo, SP, Brazil

2 Cruzeiro do Sul University/ FATEC Prof. Miguel Reale, Sao Paulo, SP, Brazil

3 Leiden University, Leiden, The Netherlands

4 Federal University of Sao Paulo, Diadema, SP, Brazil

5 National Institute for Space Research, Sao Jose dos Campos, SP, Brazil

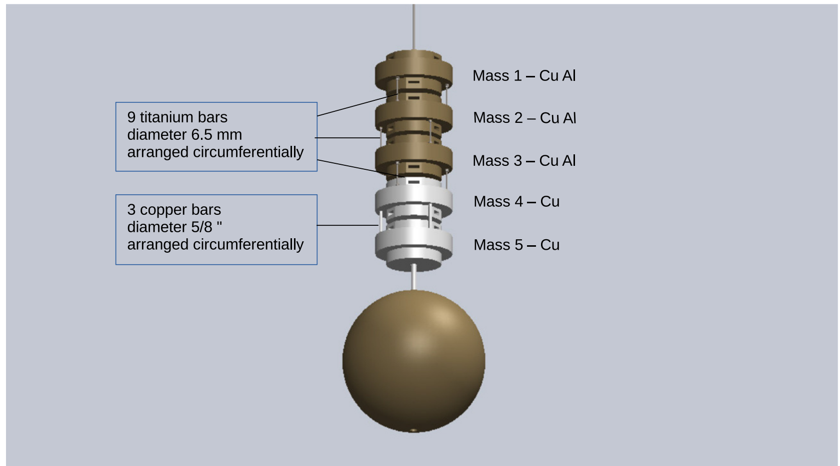

Fig. 1 General view of the suspension connected to the spherical antenna [14, 15]

us to determine the effectiveness of the suspension used in the detector. The results of our studies are presented in the following sections. More information concerning the vibrational system of the Schenberg detector can be found in reference [14].

2 The Antenna's Suspension System

Schenberg's suspension set includes its main vibration isolation system. It is responsible for the attenuation of external mechanical noise. The minimal thermal noise is reached by cooling the detector down to cryogenic temperatures. An effectively low temperature together with a good suspension system should ensure that the antenna reaches the sensitivity required to detect a possible GW signal.

The suspension system is constituted by a succession of spring-mass systems, functioning as a mechanical low-pass filter aiming at filtering the seismic mechanical noise and environmental non-seismic noise. The masses are cylindrical metal objects with masses around 120 kg, and the restorer elements (springs) are cylindrical solid rods, which connect those masses to each other.

Schematics of the suspension, connected to the sphere and exhibiting construction details [15], are shown in Figs. 1 and 2. The elements that compose it are: the upper stem made of a Ti Al V alloy, with 90 % Ti 6 % Al 4 % V; the three higher masses (mass 1, 2, and 3) made of 94 % Cu 6 % Al and joined together by a stem made of Ti Al V as mentioned above; the two lower masses (masses 4 and 5) are made of copper and connected by stems of the same material; the lower stem is connected to the sphere and is made of copper.

The suspension was constructed to avoid the production of phonons through accommodation of the material, so its structure was designed to ensure that the mechanical tensions are always much lower (from 10 to 20 %) than the yield strength of the involved materials [16].

3 The Required Vibrational Attenuation

In order to minimize the influence of the internal vibrational modes of the isolation system on the resonant modes of the sphere, it is necessary for the isolation system to present a free spectral resonance window, around the detector's characteristic frequencies.

The vibration isolation system must generate an attenuation (around 180 dB [16]) to ensure that the residual

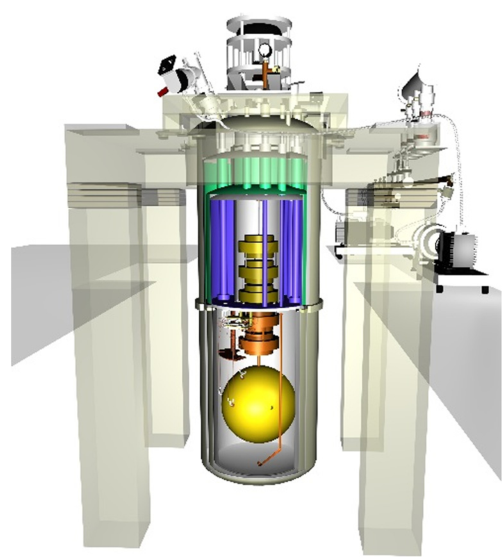

Fig. 2 Schematics of the detector inside the dewar (a container subjected to high vacuum) and the pneumatics also used to attenuate noise, connected to the upper stem (illustration by Xavier P. M. Gratens)

mechanical noise on the sphere is equal to or smaller than the spectral displacement caused by the thermal noise. The suspension vibration isolation system theoretically produces an attenuation of 300 dB at 3200 Hz [15]. An estimate of the attenuation necessary can be obtained using the thermal noise on the sphere as a target, the maximum seismic noise allowed on the sphere surface will be the thermal noise. The thermal noise spectral density can be obtained by the expression [16]:

$$x_\nu = \sqrt{\frac{2kT}{MQw^3}} \ \ (mHz^{-1/2}), \tag{1}$$

where k is Boltzmann's constant, T is the temperature, M is the antenna's mass, and Q is the mechanical quality factor for the frequencies of the normal modes of the antenna. Finally, $\omega = 2\pi f$, where f is the antenna's resonant frequency. Substituting in (1) the values for Schenberg at frequency of 3200 Hz, one finds a thermal noise density of 10^{-46} m^2/Hz. The seismic noise spectral density can be obtained by the empirical formula [16, 17]:

$$x_t = \frac{a}{\nu^2} \ \ (\text{m Hz}^{-1/2}), \tag{2}$$

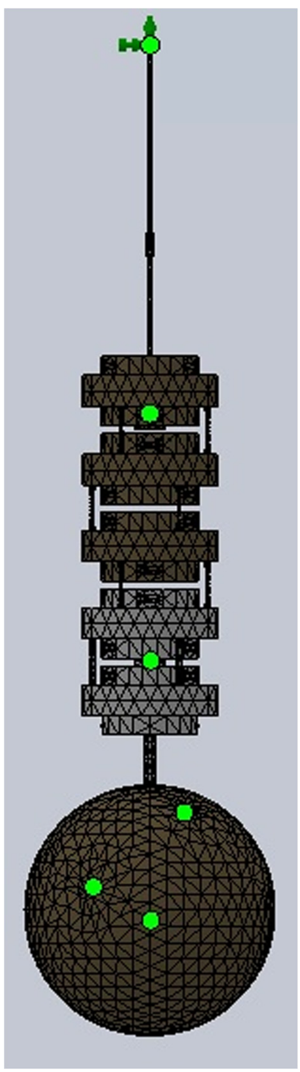

Fig. 3 The mesh that was designed and which was used in the calculations

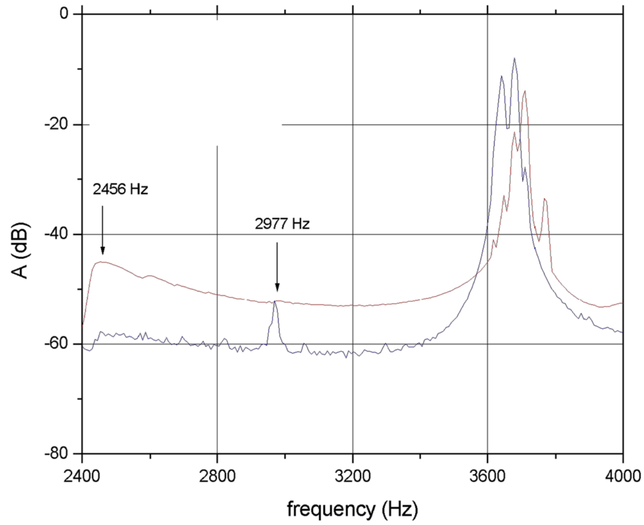

Fig. 4 Transfer function: the shaker was connected to mass 1 and the measurements were made at masses 1 and 2. The attenuation noise obtained, around the resonant frequency of the sphere, was about 10 dB

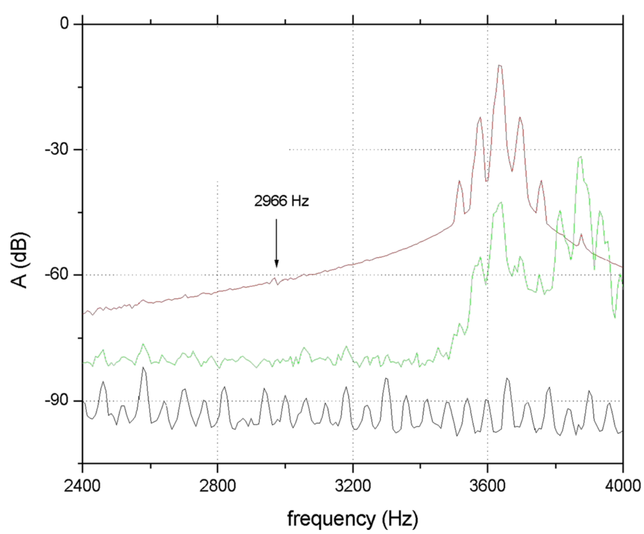

Fig. 5 Transfer function: the shaker was connected to mass 2 and the measurements were made at masses 2 and 3. The attenuation noise obtained, around the resonant frequency of the sphere, was about 20 dB

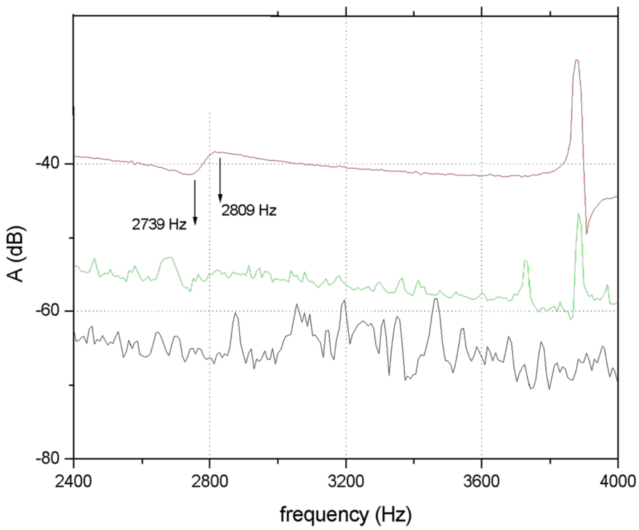

Fig. 6 Transfer function: the shaker was connected to mass 3 and the measurements were made at masses 3 and 4. The attenuation noise obtained, around the resonant frequency of the sphere, was about 15 dB

where a is the parameter that depends on the terrain and depth, which was adopted as 10^{-8} (m $\mathrm{Hz}^{3/2}$) (a value considered conservative among the surveyed options); ν is the frequency of the displacement of the ground, adopted as 3200 Hz, the detector's central resonant frequency. The substitution of the values for Schenberg into (2) yields a spectral shift due to seismic noise of 10^{-30} m^2/Hz.

In summary, for the thermal noise:

$$x_\nu \approx 10^{-46}\mathrm{m}^2/\mathrm{Hz}$$

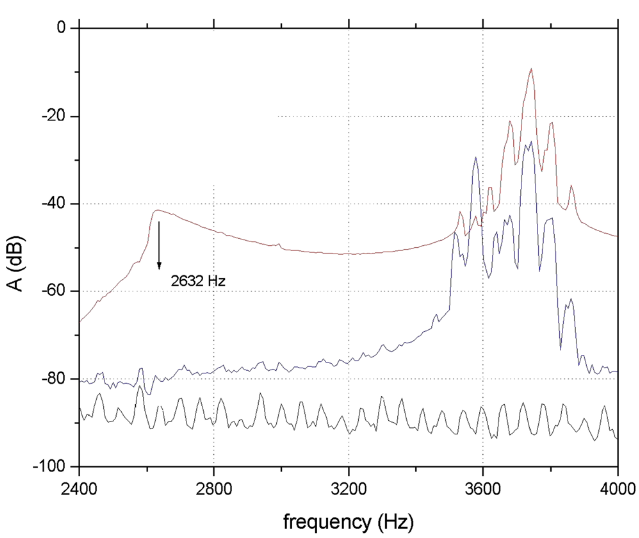

Fig. 7 Transfer function: the shaker was connected to mass 4 and the measurements were made at masses 4 and 5. The attenuation noise obtained, around the resonant frequency of the sphere, was about 30 dB

and for the seismic noise is:

$$x_t \approx 10^{-30}\mathrm{m}^2/\mathrm{Hz}.$$

Then the total attenuation needed is:

$$x > 10^{16}\mathrm{m}^2/\mathrm{Hz}\ \text{or}\ 160\ \text{dB}.$$

Therefore, for the sensitivity of the detector not to be compromised by the mechanical noise suspension, it is necessary to reach an attenuation greater than or of the order of 160 dB. In this way, the residual mechanical noise should not exceed the thermal noise.

4 Modelling and Validation

The finite element modeling was performed using SolidWorks Simulation 2010–2011 version. In order to obtain reliable results when using finite elements modeling (FEM) and before performing the simulations of the vibrational pattern of the suspension of the Schenberg detector to determine the efects of the seismic noise on the transducers, it is necessary to create a numerical model that represents the structure to be analyzed, including its internal and external constraints as well as the external conditions which the structure is subjected to. Such numerical models are made of a tridimensional mesh that contains elements appropriately linked by the user in such a way that the physical laws that describe the known behaviors of the system can be numerically accounted for. The model is considered adequate when eventually the calculations yield the desired parameters. Early in this work, in order to create the mesh, it was used the automatic process available in the software. Such mesh was then analyzed and corrected. Control rules were imposed in places where irregularities and discontinuities were found to increase or decrease the elements, after which a new mesh was designed to better satisfy the demanded conditions. Typically, such irregularities are found where significant dimensional changes of the analyzed structure appear.

The final mesh that we designed and which was used in our calculations is shown in Fig. 3. In this figure, it is possible to see changes in the elements' sizes and a few moving probes (the green dots) available in the software, which are used for sensing the I/O parameters. These probes

Table 1 Experimental values for attenuation measured between the indicated masses [15]

Masses 1 and 2	Masses 2 and 3	Masses 3 and 4	Masses 4 and 5
10 db	20 db	15 db	30 db

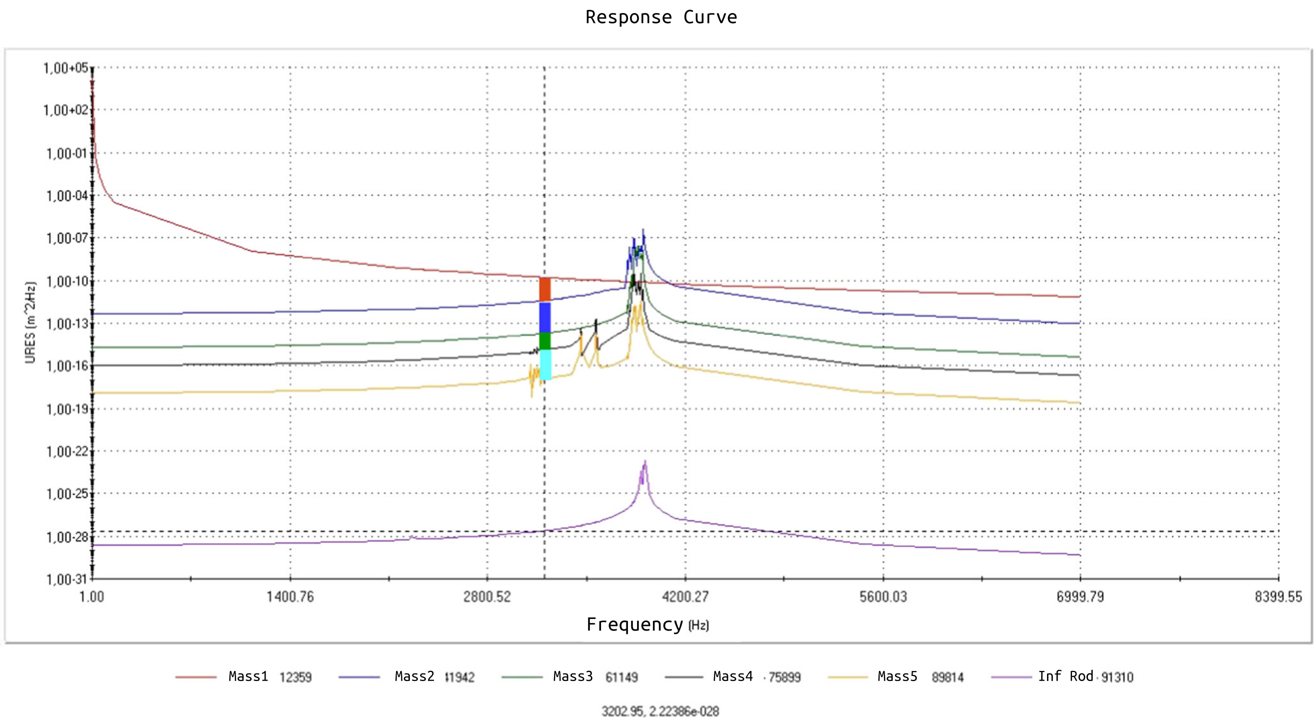

Fig. 8 Frequency response curve, obtained by simulation [14] for the model shown in Fig. 5. From *top to bottom*, the graph curves refer to localized probes: the excitation point (upper face of the first mass or higher), the upper faces of the second, third, fourth, and fifth masses. The *lower curve* refers to the location of the transducers from above. They are marked at a frequency of 3200 Hz, the attenuation obtained among the masses of the suspension

were useful, for instance, in the determination of response curves. After the mesh is designed, the model and the settings used in the program must be validated. Among the adopted configurations, we highlight the following:

Simulation properties: Number of modes: 40 Closest (frequency of interest, in Hz): 3200 Solver: automatic

The excitation that represents the local seismic noise (calculated via equation 2) was applied at the top end of the upper titanium rod.

Remote mass: The sphere was configured once as a remote mass for model validation. This option is available in the software to be used when there is no interest in analyzing other components of the structure. In other calculations, this option was not adopted, allowing the analysis of the sphere but increasing computational time as a consequence.

A modal damping of 0.0005 was used to avoid cyclic errors in the calculations in case a singularity was found.

The validation procedure compares the experimental data presented in reference [15] to the results obtained in the FEM of the equivalent system. The final goal is to compare the attenuations obtained experimentally. To this end, it is necessary to obtain first the frequency response curve from the program, so moving probes (available in the FEM program as sensors) were introduced in the same positions where experimental measurements were made. An

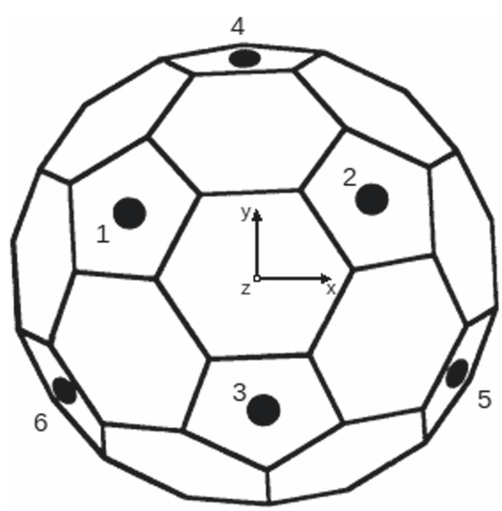

Fig. 9 Positions of the six mechanical impedance matchers used in the Schenberg detector relatively to the surface of a truncated icosahedron

Table 2 Positions of the six mechanical impedance matchers, in spherical coordinates, on the surface of the spherical antenna

Mechanical impedance matchers	1	2	3	4	5	6
ϕ (°)	150.000	30.000	270.000	90.000	330.000	210.000
θ (°)	52.622	52.622	52.622	10.811	10.811	10.811

excitation was applied on top of the first mass (mass 1) corresponding to the excitation seismic noise, which was estimated for all studied frequencies. The transfer functions relative to four experimental measurements are shown in Figs. 4, 5, 6, and 7, while the corresponding values of attenuation [15], measured between the suspended masses, are shown in Table 1.

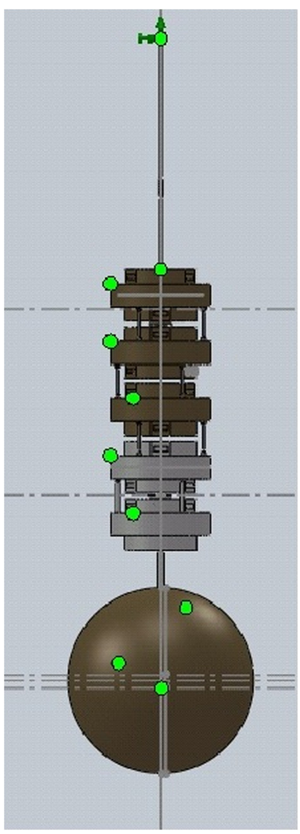

Fig. 10 Model used in this simulation. The *points highlighted* indicate the positions of mechanical impedance matchers. The two points on the surface of the sphere, on its upper hemisphere, were placed at the same locations of the transducers

The validation procedure compares the experimental values presented above to the results obtained in the FEM of the equivalent system shown in Fig. 3. The response curve obtained through the simulation is shown in Fig. 8, where the values for the attenuation between the masses of the suspension, obtained through the experimental measurements, were color-marked at the frequency of 3200 Hz; the red mark represents the attenuation from the first to the second mass, the dark blue mark represents the attenuation from the second to the third mass, the green mark represents the attenuation from the third to the fourth mass, and the light blue mark shows the attenuation from the fourth to the fifth mass. The results of the finite element modeling are reasonably consistent with the experimental data, indicating that the settings are suitable to be used and therefore, the validation was successful.

5 Seismic Noise on the Sphere Surface

In order to obtain the value of attenuation of the seismic noise influence on the sphere surface of the sphere at the positions of the transducers are actually located, vibrations were numerically implemented in the simulated suspension of Schenberg.

Since the suspension of the connection point to the external environment is in the region near the top of the upper rod, the excitation was applied to the upper face of this rod with the same values applied in the previous simulation, obtained by (2).

In order to determine the attenuation produced by the excited point and the transducers, simulated motion sensors (mechanical impedance matchers) were added to the model at positions corresponding to those of the actual transducers. These positions are shown in Fig. 9 and Table 2. Figure 10 shows the schematics of the model used in this simulation.

Figure 11 displays the frequency response graph to the model's various sensors, including those located on the surface of the sphere, obtained for an excitation similar to the seismic noise one. The frequency response curves were obtained after application of an excitation similar to the seismic noise on the top of upper stem. Observing the resulting values for the probe at a frequency of 3200 Hz, it is possible to identify an attenuation in the spectral displacement of nearly 10^{16} m^2/Hz or 160 dB. As an additional attenuation of approximately 10^3 m^2/Hz is expected to be generated by the tire shown in Fig. 2, the total attenuation, down to where the transducers are connected (on the surface of the sphere), according to the results

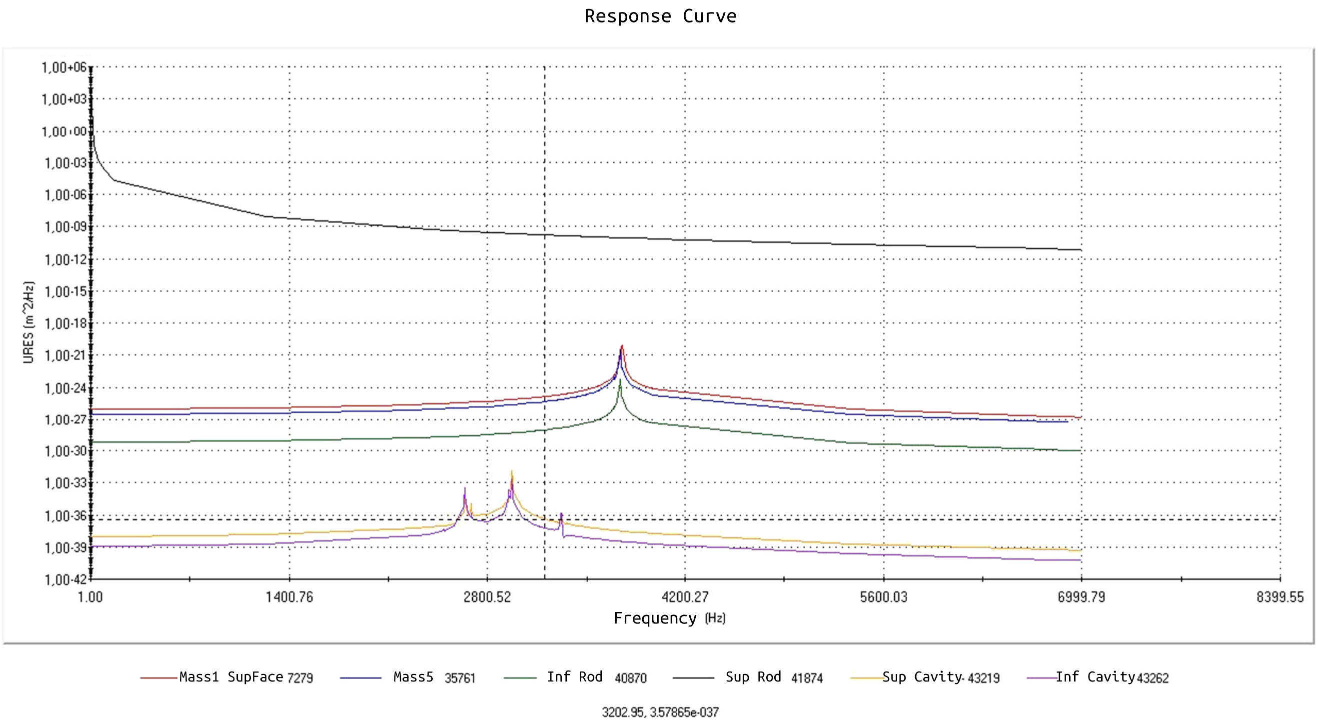

Fig. 11 Response graph showing, in the two lower curves, the result obtained for the spectral displacement of sensors located on the surface of the sphere. Observing the values resulting from these two probes at a frequency of 3200 Hz, it is possible to identify an attenuation of nearly 10^{16} or 160 dB

obtained, will be sufficient to ensure the needed sensitivity of the detector.

6 Concluding Remarks

In this work, the suspension designed and built for the Schenberg detector was modeled using the finite elements method. The motion sensor used in the model yielded an attenuation between the upper face of the support suspension stem and the transducers on the surface of the sphere that is sufficient to allow thermal noise not to be exceeded by the seismic noise. Moreover, since the pneumatics as well as a large mass about 4 metric ton that take part of the actual suspension were not considered in the simulation due to existing computational limitations, the total attenuation provided by the suspension system is expected to be even better.

As a natural continuation of this work, the FEM could include the pneumatics and the large mass of the support antenna structure. Moreover, the sphere should be considered with the holes that are used to attach the transducers to it. Also, a multimode impedance matcher should be investigated, aiming at modeling the actual, double-mode transducer planned to be used in Schenberg.

Acknowledgments CF acknowledges FAPESP (grant # 2010/00167-4) and CNPq (grant # 312906/2013-7) for the financial support.

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