INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **21** (2004) S999–S1003 PII: S0264-9381(04)68020-8

The antenna–transducer mechanical coupling design for the Schenberg detector

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Received 27 August 2003
Published 11 February 2004
Online at stacks.iop.org/CQG/21/S999 (DOI: 10.1088/0264-9381/21/5/092)

Abstract

We are designing microwave parametric transducers to be used in the Brazilian gravitational wave detector. In this paper, we explain the technical constraints used to design the mechanical parts of these transducers. The transducer and the antenna have been modelled by a finite element model (FEM) and the corresponding dynamical equations have been solved using the Msc/Nastran software. We have used the FEM analysis results in an iterative way, adjusting the geometric parameters in each step. Using this procedure we were able to calculate the transducer mechanical structure by positioning its main resonance frequency to the value of the sphere's quadrupolar mode frequency in order to design the best possible mechanical coupling and increasing transducer efficiency.

PACS number: 04.80.Nn

1. Introduction

The very small characteristic amplitudes ($\sim 10^{-22}$ m$\mathrm{Hz}^{-1/2}$) of gravitational waves of astrophysical origin [1] impose hard constraints on the design of resonant gravitational wave detectors. In typical cases, the gravitational signal will only produce a very small vibration on the resonant mass, which corresponds to the very small amount of energy transferred from the wave [2, 3]. Therefore, the energy transfer between the resonant mass and the transducers used to pick up the gravitational signal is a very critical process that must be as efficient as possible.

The Schenberg detector resonant mass is a 1.15 ton CuAl6% sphere with a diameter of 65 cm and a central hole used to fix the suspension cable (figure 1). Finite element

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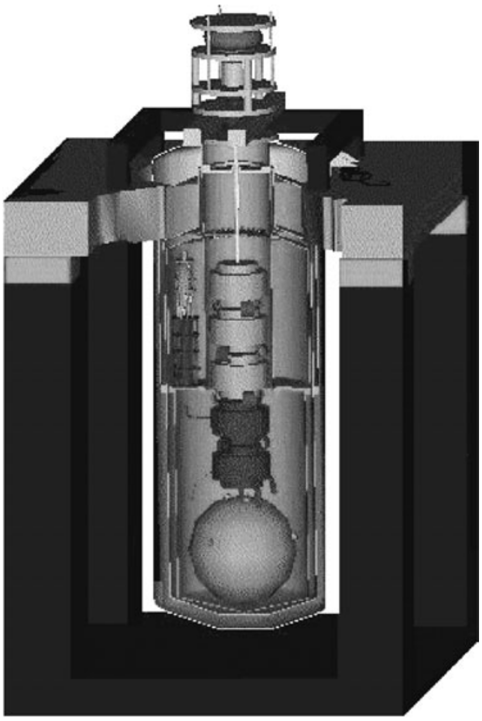

Figure 1. The Schenberg detector. It shows the support structure, the cryogenic system, the five modules of the vibration isolation system and the transducers attached to the sphere surface.

method calculations showed that this geometrical configuration reveals the five components (between 3100 Hz and 3300 Hz) of the sphere's first quadrupolar modes. If gravitational waves reach the sphere, these modes can be excited and it is possible to measure their resonances. Parametric transducers attached to the sphere surface will be used to convert the mechanical vibrations, produced by the gravitational waves, into electrical signals. To achieve the necessary sensibility the mechanical system must have a mechanical Q over 1 million and, of course, a very efficient vibration isolation system is necessary. Finite element simulations have showed [4] that, with the vibration isolation system designed for the Schenberg detector, it will be possible to obtain more than 300 dB of attenuation in the spectral region around the calculated sphere quadrupolar resonances. This attenuation level guarantees that the small amount of energy transferred from the gravitational waves to the sphere will be distinguishable from the remaining noise. So, a non-efficient transducer pick-up process would represent the waste of the precious signal revealed by the mechanical resonance. Therefore, it is imperative to have the best mechanical coupling between the sphere and the transducers in order to maximize the energy transfer. This paper describes the design approach used to obtain the best possible coupling.

2. Parametric transducers

Six parametric transducers [5], tuned to the first five quadrupolar modes of the sphere, will be attached to the resonant mass of the Schenberg detector inside holes distributed on the sphere surface. Each parametric transducer is made up of a very high electrical Q microwave cavity mounted on a mechanical structure composed of two high mechanical Q resonators. The attachment of this structure to the sphere will be performed by differential thermal contraction since niobium, the material from which the transducers will be made, contracts less than CuAl6%. The fundamental mode frequencies of both these resonators must be adjusted to the value corresponding to the mean of the five sphere quadrupolar mode frequencies. Consequently, if a hypothetical gravitational wave excites the sphere's quadrupolar modes, the corresponding mechanical energy will be transferred from the sphere to the transducers. The transducers will be very light ($\sim$100 g) compared to the sphere and therefore the transferred energy would produce increasing amplitudes in the first and second transducer resonators. The microwave cavity will have a very thin, light, front wall that will correspond to the second transducer resonator. When excited by the sphere's resonance, this kind of membrane will vibrate and its vibration will modulate a microwave carrier signal injected into the cavity. This modulation can then be extracted from the microwave signal and its measurement will contain the gravitational information. Of course, the energy transfer from the sphere's quadrupolar resonances to the transducer's first resonator and then to the second resonator corresponds to a critical process which must be as efficient as possible. The efficiency of this process corresponds to the best possible tuning between the frequency of the transducer modes and the sphere's quadrupolar modes, and to the largest possible transducer mode shape amplitudes. To carry out these two design conditions, it is necessary to propose and calculate different geometric transducer configurations in order to obtain an adequate mechanical structure.

3. Transducer mechanical structure

The proposed mechanical transducer structure is composed of two masses, an external ring and an internal cylinder, joined together by six rigid springs. The system formed by the internal cylinder and the springs corresponds to the first resonator. The microwave cavity will be built on the centre of the internal cylinder. This cavity will have a very thin front wall that will play the role of the transducer's second resonator. Both the resonators must be tuned to the same frequency of the sphere's quadrupolar modes. The external ring will be attached to holes in the sphere. The mass of the internal cylinder and the thickness of the springs determine the transducer's first resonator frequency. The frequency of the cavity membrane is basically determined by its thickness and diameter. So, by adjusting these geometric parameters is possible to tune the transducer resonant frequencies. An initial proposed geometric configuration for the transducers has been represented as a finite element model and the corresponding differential equations have been solved using the Msc/Nastran software. The best geometric set-up for the transducers has been determined by analysing the results of FE models and adjusting the geometric parameters successively in an iterative design procedure [6]. Several dynamical analyses have been made in order to adjust the transducer's main longitudinal resonant frequency, positioning it at the mean of the sphere's quadrupole mode frequencies and looking for larger mode shape amplitudes of the first and second transducer resonators.

The best set-up we obtained was achieved when the diameters of the external ring and the internal cylinder (figures 2–4) were 3 cm and 2 cm, respectively, and the thickness of the rigid springs was about 2 mm. With this configuration, the transducer calculated mechanical resonant frequency is $\sim$3285 Hz, almost at the centre of the calculated sphere resonances.

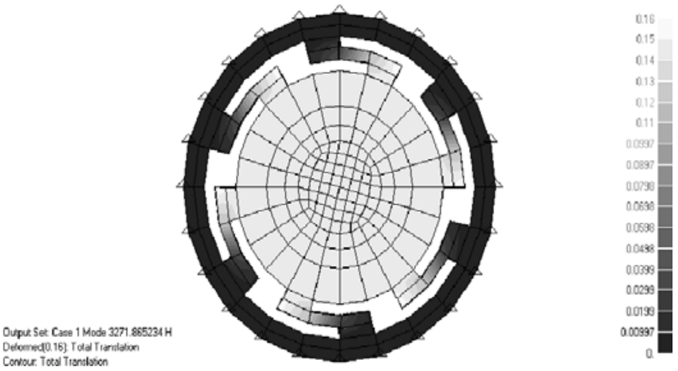

Figure 2. Transducer top view.

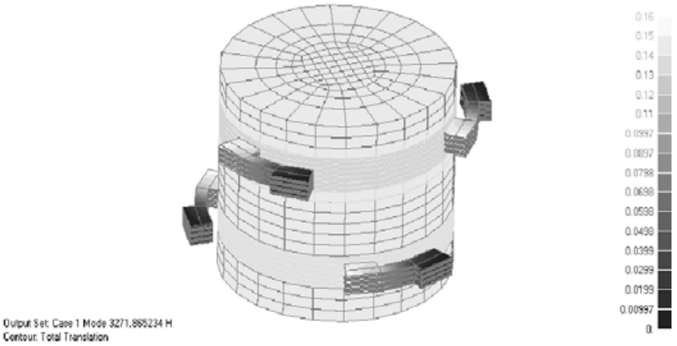

Figure 3. Transducer body without the external ring showing the springs of the first resonator.

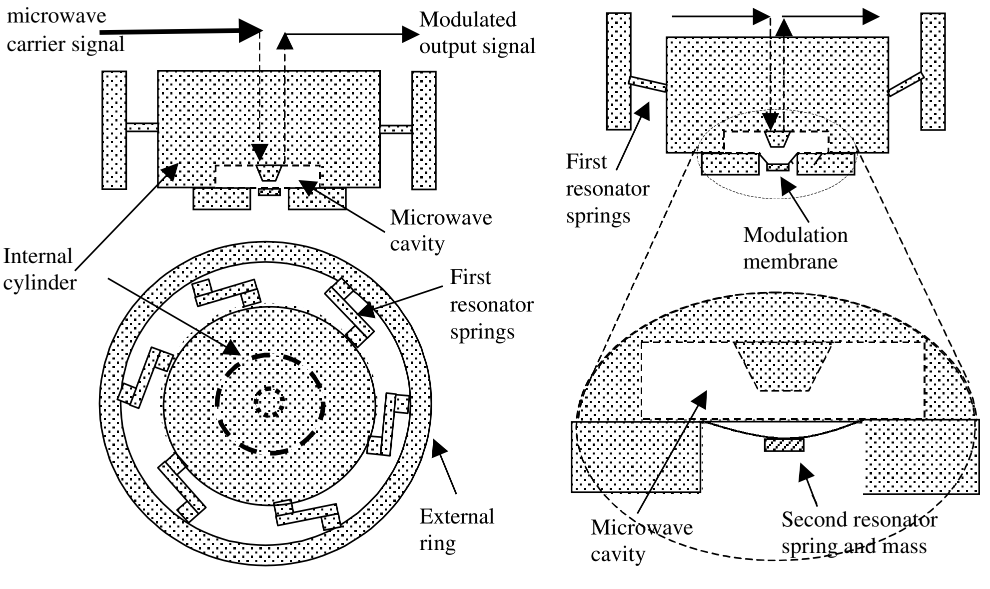

Figure 4. Microwave parametric transducer. The vibration amplitudes have been enlarged to clarify the schematics.

4. Conclusion

The iterative design procedure, using FEM to simulate the mechanical behaviour, which has been used to calculate the large, heavy structures of the Schenberg detector vibration isolation system [7], has also allowed the design of its small and light transducers. This design procedure has produced a mechanical structure tuned to the sphere's quadrupolar central frequency (3285 Hz), and since the springs are very thin and the second resonator has been conceived as a very thin membrane, the mode shape amplitudes have been maximized. The fulfillment of these two design constraints corresponds to the best mechanical coupling found between the sphere and the transducers, and results in an efficient energy transfer process. However, the dimensions must be re-adjusted in the future in order to tune the transducer resonant frequency to the exact experimental values of the sphere's quadrupolar mode frequencies. These experimental values will be measured at 4.2 K during the first cooling down run. Other adjustments will also be necessary after the final design of the microstrip antenna and of the first resonator assembly. Only then we will have the final transducer dimensions.

Acknowledgments

The authors would like to thank FAPESP (grants nos 1998/13468-9 and 2001/12606-3), CNPq (grant 300619/92-8) and MCT/INPE.

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