Measurement of mechanical vibrations in a solid aluminium sphere and bar excited by 0.5 GeV electrons.


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We have measured mechanical vibrations induced by 0.5 GeV electrons impinging on a aluminium sphere and bar. The results agree with the thermo acoustic conversion model.

Introduction

A key issue for the GRAIL proposal, a three meter diameter copper sphere to be operated at 10 mK for detecting gravitational waves, is the background arising from cosmic rays. The energy deposited in the sphere along a particle's track may excite the very vibrational modes that are to signal a passing gravitational wave. Computer simulations of such effects are based on the earlier measurements of Beron and Grassi Strini et al and on their thermo acoustic conversion model, which holds that the energy deposited along the track of a traversing particle would heat the material and thus lead to tensions exciting the acoustic vibrational modes. At the strain sensitivity of $5 \times 10^{-21}$ envisaged, simulations show that operating the instrument at the surface of the earth would be inhibited by the effect of the cosmic ray background. However, shielding the instrument by some layer of rock as available in the Gran Sasso laboratory would suppress the cosmic ray background sufficiently. So it would be of particular importance for the prospected shielding of GRAIL that Nautilus succeeds in measuring the cosmiccos correlations at the expected increased antenna sensitivity. We set out to reproduce and extend the earlier measurements on which the model is based.

Experiment

A 0.20 m long aluminium bar of 0.035 m diameter was horizontally suspended with a string around its waist from a construction to remotely move the bar horizontally, and let the beam hit it at different places along its cylinder axis. The construction was fixed to an aluminium four-ped inside a vacuum chamber at $10^{-5}$ mbar. The four-ped could be rotated and moved vertically to

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also let the beam pass the bar completely. One Philips PXE5 piezo sensor of 3*6*0.3 mm$^3$ was glued with a cyanoacrylate parallel to the end face on the cylinder axis, a second one parallel to the cylinder surface at 35 mm more inward, and a piezo hammer at the opposite end face. Each sensor was connected to a charge amplifier of $2 \times 10^{10}$ V/C gain. The signals were sent through a low pass 100 kHz pre-filter, to a type R9211C Advantest spectrum analyser with internal 2 MHz presampling and 125 kHz digital low pass filtering. The oscillations were recorded for 64 ms periods at a 4 $\mu$s sample rate, corresponding to $\Delta f = 15$ Hz frequency resolution, were stored on disk and were fourier analysed off line.

We used the MEA 8 20 mA peak current electron beam with a pulsewidth of up to 2 $\mu$s in single shot mode, each pulse containing $\approx 5 \times 10^{10}$ electrons of $\approx 0.6$ GeV. The beam current and duration were recorded by a calibrated digital oscilloscope, photographed and analysed off line.

In another experiment a sphere of 0.15 m diameter was suspended by a brass rod of 0.15 m length and 2 mm diameter, from its centre. The rod was supported by the same four-ped. Two piezo sensors were glued to the sphere's surface, one at the equator, the other one at a relative displacement of 450 west longitude, and at 450 north latitude. A piezo hammer was mounted diagnostically to the latter. The beam electron energy was $\approx 0.35$ GeV.

The experiments were done at room temperature.

Experimental results

Sensor signals well above the noise were observed for every beam pulse hitting the sphere or bar. The ascertainment that a) the signals arise from mechanical vibrations in the sphere, and b) are directly initiated by the effect of the beam on the sphere, not indirectly by an electromagnetic effect on the piezo sensors, is grounded on a combination of test results, observed mostly for both the bar and the sphere. Firstly, when the beam passes underneath the sphere or bar, without hitting it, we observe no signal above the noise. Secondly, the sensors delayed responses agree with the sound velocity, as shown in fig. 1, where the beam is hitting the sphere at a position 5 mm above the sphere's south pole. The middle trace shows the beam pulse of $\approx 2 \mu$s duration. The distance of the equatorial sensor to the beam is 0.11 m, corresponding to 18 $\mu$s travel time for a sound velocity of $\approx 6 \times 10^3$ m/s. The fastest signal, which would come from a toroidal mode, is indeed seen in the lowest trace to start at that time after arrival of the beam. The upper trace shows the signal from the second sensor on the northern hemisphere situated at 0.14 m from the traversing beam, to arrive at 23 $\mu$s. Thirdly, when we dismount the piezo-hammer, the signals do
not change showing that the activation is not caused by a beam-induced triggering of the piezo-hammer. Further, simulating the beam pulse, we coupled a direct current pulse of 60 mA and 2.5 μs duration from a pulse generator to the bar. Apart from the direct response of the piezo-sensor during the input pulse, no signal is detected above the noise. Lastly, the measured dependence on the hit position of vibrational modes amplitudes, as to be described in the next section, follow the patterns as calculated with the thermo-acoustic conversion model.

Results for the bar
In fig. 2 a typical fourier spectrum is shown for the bar up to 45 kHz. The arrows point to the three lowest longitudinal modes, and the calculated frequencies agree within Δf = 20 Hz with the measured values, for a fitted value of the Poisson ratio ρ = 0.364, and the sound velocity c_l = 5071 m/s. Thus we take the peaks to correspond to the lowest three longitudinal vibrational modes of the bar. Other peaks correspond to torsional and flexural modes where the largest peak may point to constructive interference of a specific torsional and flexural mode calculated to fall within Δf = 3 Hz.

The fourier amplitudes A_k of f(t) = ∑ A_k e^{iωt} of the modes depend linearly on the integrated beam charge in the pulse for a fixed beam position, so on the energy deposited by the beam, which ranges from 1.5-7.5 J. The spread in the ratios of the amplitudes to the beam charge, show the fourier amplitudes to reproduce within ± 10%. Fig. 3 shows the measured fourier amplitudes of the bar at the end face piezo sensor, and the calculations following Grassi Strini et al. as a function of the hit position along the cylinder axis for the three lowest longitudinal modes. We used c_l = 5071 m/s and ρ = 0.364 as found in
our fit, and corrected the hit positions by an overall offset of 1 cm.

Fig. 4 shows the measured maximum values of the Fourier amplitudes and the model calculations $A_k$ following Grassi Strini et al. for the five lowest longitudinal modes of the bar. The calculated values were normalized to the first mode, showing agreement for the third and fifth mode, and we take the deviation as the error estimate. An appreciable damping for the even modes is seen, whereas these modes should be noted to have a maximum amplitude at the bar's waist, the very position of the suspension string.

The damping of the even modes is noted also in the decay times, which were measured by registering the sensor signals after a trigger delayed by up to 0.5 s at a fixed beam hit position. An exponential fit $A(t) = A_0 \times e^{-t/\tau}$ to the mode amplitudes gives $\tau = (0.10 \pm 0.03)$ s for these odd modes, and $\tau = (0.03 \pm 0.02)$ s for these even modes.

Results for the sphere

Our measurements on the sphere consisted of a) hitting the sphere with the beam at one of three heights in the vertically oriented plane through its suspension: at the equator (E), at about half way southward (A), and practically at the south pole (S); b) rotating the sphere with its two fixed sensors over 180° by steps of 10° around the suspension axis at each beam height. A typical Fourier spectrum is shown in fig. 5. The lowest $L=2$ mode is expected at 17.6 kHz, the lowest $L=0$ at 37 kHz, and peaks corresponding to $L \geq 1$ at $\approx 24, 26, 34, 45$ kHz.

The Fourier amplitudes, again, show a linear dependence on the deposited energy. For the decay times at $f=17.6$ and 26 kHz measured by up to 2 s
delayed triggering of the spectrum analyzer, we found $\tau \approx 1.5$ s, at other frequencies mostly 0.2-0.7 s.

Though the fourier amplitudes would depend on the mixture of degenerated M-projections for any multipole order, our Monte Carlo simulations indicate that mainly the M=0 and M=1 submodes would be excited in this specific situation. The measured angular dependence of the $f=17.6$ kHz amplitude, supposedly the lowest quadrupole mode, is shown in the upper part of fig. 6, and for the $f=37$ kHz, supposedly the lowest monopole mode, in the lower part. An analysis of the measured angular dependences with M-mixture is in progress.

**Calibration**

For a rough calculation of the sphere's absolute displacement, we firstly use our results for the bar as a calibration of our measuring device by taking the results of Grassi Strini et al. for an absolute scale and assume the sensitivity of the piezo sensors to be the same as for the sphere, finding the displacement to be of the order of magnitude as that of the bar, for the same amount of energy deposited, that is 1-10 nm/J. Secondly, with the piezo sensor's effective mass being taken 20 mg, and assuming that it measures the force, we calculate from the measured signal of $\approx 0.25$ V, at $\approx 2$ J energy deposit, and the specs for the piezo sensor's sensitivity ($2 \times 10^{-10}$ C/N) and amplifier gain ($2 \times 10^{11}$ V/C), a value of $\leq 15$ nm/J at 17 kHz. We are trying to improve the precision, by a direct calibration.
Conclusion

From a combination of observations on the bar and the sphere we have assessed that mechanical vibrations were indeed excited by the electron beam. The energy dependence and the dependence on the beam hitting position agree with the thermo acoustic conversion model of Beron et al.\(^2\) and Grassi Strini et al.\(^3\), a model that predicts a sphere's quadrupole mode to be significantly excited by cosmic rays\(^4,5\).

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