Oscillators for free-mass gravitational antennas

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The potential sensitivity of gravitational antennas using free masses could be improved significantly by fabricating their sensors, which are low-frequency mechanical oscillators, completely from fused quartz. An oscillation damping time of 1.2×10^7 s has been achieved for such oscillators. In this case the sensitivity in ordinary coordinate measurements may be limited by the standard quantum limit, rather than by thermal noise.

The sensitivity of gravitational antennas is known to improve as the fluctuational effects of the thermostat on the test masses M are weakened (see, for example, the reviews by Thorne[1] and Braginskiĭ[2]). The antenna sensitivity which has been achieved in various laboratories at this point is, in dimensionless metric-variation units h, $(1-4)\times 10^{-18}$. This sensitivity is determined to a large degree by the extent to which it is possible to lower the temperature T and to reduce the friction coefficient $H(\omega)$, which determines the dissipative coupling of the mass M with the thermostat. If we consider this effect alone, we can estimate $(h_{\min})_T$ from the simple condition

$$\left(\frac{1}{2}(h_{min})_T M L\omega_g^2\right)^2 \gtrsim \int\limits_{\omega_g-\frac{1}{2}\Delta\omega_g}^{\omega_g+\frac{1}{2}\Delta\omega_g} \frac{2}{\pi}k_B T H(\omega)d\omega, \tag{1}$$

where k_B is the Boltzmann constant, L is the distance between the test masses, ω_g is the average frequency of the expected burst of gravitational radiation, and $\Delta\omega_g$ is the spectral width of the signal. [For most burst scenarios which have been considered we would have $\omega_g \simeq \Delta\omega_g \simeq 2\pi(\tau_g)^{-1}$.]

To achieve small values of $H(\omega)$ we should evidently seek gravitational-antenna sensors which are mechanical oscillators with a resonant frequency ω_M as low as possible, and which are made from a material with a value of $\Phi(\omega)$ (the imaginary part of the Young's modulus) as small as possible. In other words, we are interested in a high quality factor $Q_M = M\omega_M H^{-1}(\omega_M) = \Phi^{-1}(\omega_M)$. Under the condition $\omega_M \ll \omega_g$, such antennas are usually called "free-mass antennas." Included in this category are antennas with a laser system for measuring the distance between masses[3,4] and antennas with QND velocity meters.[5] To the best of our knowledge, there has been no detailed study aimed at determining the minimum achievable values of $H(\omega)$ [or the maximum achievable values of $\tau_M^* = 2MH^{-1}(\omega_M)$]. In this letter we report some experimental results in this direction, and we discuss possible implications.

Several torsional oscillators were fabricated and tested. Each was a cylinder suspended from a thin filament. The mass of the cylinder ranged from 30 to 10^3 g, the diameter of the filament ranged from 150 to 500 μm, the length of the filament was 30 cm, and the resonant frequency ω_M ranged from 0.5 to 5 s^{-1}. Fused quartz was selected as the material. A quality factor $Q_M = (1\text{–}3)\times 10^7$ had already been achieved[6] for the relatively high frequencies $\omega_M = 10^3\text{–}10^4\ s^{-1}$ for this material. In addition, this choice made it possible to fabricate the entire oscillator from one material and thereby avoid an additional energy loss at the point at which the elastic element is connected to the mass.

The largest value of τ_M^* was reached under the following conditions: (a) Quartz with the lowest impurity content was used. This matrial made it possible to achieve $Q_M \geqslant 10^7$ at $\omega_M \simeq 10^3\ s^{-1}$. (b) The quartz filament was heated in an oil-free vacuum at 250 °C for at least 5 h in order to remove adsorbed molecules from the surface. (c) The oscillator was attached to the upper support through a massive slab, also made of quartz. The filament was welded to this slab. The "discontinuity" in mechanical impedance which arises as a result is required in order to reduce the dissipation in the support, as can be easily shown.

Under these conditions it was possible to achieve a damping constant

$$\tau_M^* = (1.2 \pm 0.1)\times 10^7\ \text{s}. \tag{2}$$

Corresponding to this value of τ_M^*, with $M = 30$ g and $\omega_M = 1.1\ s^{-1}$, are the values $Q_M \simeq 7\times 10^6$ and $H(\omega_M) \simeq 5\times 10^{-6}$ g/s.

The laser system used for detecting the damping in these experiments made it possible to attain the specified error in the measurement of τ_M^* over a measurement time of about 3×10^4 s against the background of ordinary microseisms.

In order to calculate the thermal noise of a gravitational antenna which uses an oscillator with the damping time τ_M^* attained, we need to know the coefficient $H(\omega)$ at frequencies $\omega \simeq \omega_g \simeq 10^3\text{–}10^4\ s^{-1}$, well above $\omega_M = 1.1\ s^{-1}$. Unfortunately, no methods are available for measuring this quantity for high-quality-factor oscillators. On the other hand, it can be estimated from the value of $H(\omega_M)$ at the resonant frequency ω_M. The results of these experiments, along with other data on the damping of elastic vibrations in fused-quartz oscillators with resonant frequencies in the range $\omega_M = 1\text{–}10^5\ s^{-1}$, show that the imaginary part of the Young's modulus of the material, $\Phi(\omega)$, depends only weakly on the frequency in this interval. Since we have $H(\omega) = M\omega_M^2\omega^{-1}\Phi(\omega)$, we can assume $H(\omega) \leqslant H(\omega_M)$ at $\omega > \omega_M$.

Extrapolating these results, we can estimate the potential sensitivity of gravitational antennas with relatively small test masses and small values of L. With $M = 10^4$ g and $L = 3\times 10^2$ cm, we find $h \simeq 10^{-20}$, even at $T = 300$ K. When the length of the filament is increased and the value of ω_M is reduced, we could presumably achieve larger values of τ_M^*.

Another important circumstance is associated with the value attained for τ_M^*. As the fluctuational effects of the thermostat on the test mass are weakened, the sensitivity to an external agent is limited by the so-called standard quantum limit.[1,2] The condition for reaching this limit is simply

$$\frac{2k_B T\tau^2}{\tau_M^*} \lesssim \hbar, \quad (3)$$

where τ is the time expended on the measurement. For gravitational antennas, this time must be $\simeq 2\pi\omega_g^{-1}$. With $\tau = 3\times 10^{-4}$ s, condition (3) is satisfied at the value $\tau_M^* = 1.2\times 10^7$ s which has been attained, even at $T = 300$ K. We would point out that the standard quantum limit must not be regarded as an insurmountable limitation on the sensitivity of gravitational antennas. Here it is necessary to use some appropriate measurement procedure—something other than simple coordinate measurements.

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