**New Folder Name** Oscillators

"The Oscillators for the Free Mass Gravitational Wave Antennae," by V. B. Braginsky, V. P. Mitrofanov, and O. A. Okhrimenko

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This contains Braginsky's recent experimental results on the Q of fused silica



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# THE OSCILLATORS FOR THE FREE MASS GRAVITATIONAL WAVE ANTENNAE.

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It is shown that the potential sensitivity of free mass gravitational radiation antenna can be significantly increased if the antenna test mass oscillator is made "all-silica".

The obtained damping time of the prototype oscillator is $\tau^{*}_{M} = 1.2\cdot 10^{7}$ s. With such damping times, the effect of thermal noise on the sensitivity of antenna with coordinate meter will be reduced below the level determined by standard quantum limit.

It is well known that the sensitivity of gravitational wave antenna is limited by its coupling to the heat bath: the gravitational force acting on test mass M must be greater than the Nyquist force ( see reviews [1,2] ). The achieved sensitivity of existing antennae is between $h=(1-4)\cdot 10^{-18}$ in dimensionless units of metric perturbation. To considerable degree this value is determined by the temperature T of the heat bath and the friction coefficient H that couples the mass to the heat bath. Taking into account only this effect one can estimate $( h_{min} )_T$, using the following simple condition:

$$\left( \frac{1}{2} (h_{min})_T \, M \, L \, \omega_{gr}^2 \right)^2 \gtrsim \int_{\omega_{gr}-\frac{1}{2}\Delta\omega_{gr}}^{\omega_{gr}+\frac{1}{2}\Delta\omega_{gr}} \frac{2}{\pi} k_B \, T \, H(\omega) \, d\omega \qquad (1)$$

where $k_B$ is the Boltzmann constant, L - the distance between test masses, $\omega_{gr}$ - the average frequency of expected gravitational radiational burst, $\Delta\omega_{gr}$-signal bandwidth (for the majority of known astrophysical bursts scenarios $\omega_{gr}\simeq\Delta\omega_{gr}\simeq 2\pi(\tau_{gr}^{-1})$).

It is evident that in order to achieve low $H(\omega)$, the gravitational wave antenna test mass oscillator must have low eigenfrequency and be manufactured of the material with low value imaginary part of Youngs modulus $\Phi(\omega)$ ( where $\Phi^{-1}(\omega)=M\,\omega_M\,H^{-1}(\omega_M)=Q_M$). The antennae with $\omega_M \ll \omega_{gr}$ are usually called free mass antennae. Lazer interferometric antennae [3,4] and antennae with QND speed meter [5] can be attributed to this type of detectors.

To the authors knowledge, a detailed study of accessible minimum value $H(\omega)$ and, therefore, maximum $\tau^*_M = 2\,M\,H^{-1}(\omega_M)$ has not been carried out to date. The experimental results of investigation of this kind with discussion are given below.

A number of torque oscillators consisting of cylinders with fiber suspensions were manufactured and tested. The mass of cylinder was 30 - $10^3$ g, the diameter of fiber - 150-500 $\mu$m, the fiber length-30 cm, $\omega_M \simeq 0.5-5\ s^{-1}$. Fused silica was chosen as the material for both cylinder and suspension because the value $Q_M = (1-3)\ 10^7$ has been already obtained for the fused silica oscillators at the relatively high frequencies $\omega_M = 10^3 - 10^4 s^{-1}$ [6]. Furthermore, application of this material permits to manufacture the "all-silica" oscillator, avoiding the losses of energy in the point where fiber is attached to cylinder.

Maximum value of $\tau^*_M$ was achieved under the following conditions: a) fused silica with the lowest quantities of impurities was used ($Q_M = 3 \cdot 10^7$ has been already obtained for the oscillators from this material at frequencies $\omega_M = 10^3 - 10^4 s^{-1}$); b) silica fiber was heated in the oil-free vacuum during 5 hours to remove the absorbed molecules; c) fiber was welded to massive fused silica support to realize the leap of mechanical impedance and decrease the dissipation of energy in support.

Keeping these conditions we succeeded to achieve the damping time

$$\tau^*_M = (\ 1.2 \pm 0.1\ ) \cdot 10^7\ s \qquad (2)$$

This value of damping time corresponds to the $Q_M \simeq 7 \cdot 10^6$ and $H(\omega_M) \simeq 5 \cdot 10^{-6}\ g\ s^{-1}$ ( $M = 30$ g, $\omega_M = 1.1\ s^{-1}$).

It is appropriate to note that the employed laser registration technique in presence of usual microseismic disturbances allowed to measure the damping time with the above-mentioned accuracy in $3 \cdot 10^4$ s.

In order to calculate the thermal noise of gravitational wave antenna test mass oscillator with the damping time achieved in our experiment, it is necessary to know the value of the friction coefficient $H(\omega)$ at frequencies $\omega \simeq \omega_{gr} \simeq 10^3-10^4$ $s^{-1}$ ( significantly larger then $\omega_M=1.1$ $s^{-1}$).Unfortunately there are no methods to measure this value for high-Q oscillators. Nevertheless it can be evaluated from the value $H(\omega_M)$ at the oscillator eigenfrequency $\omega_M$.The results of the reported experiment along with other data on elastic energy dissipation in fused silica oscillators at frequencies $\omega_M=1-10^5$ $s^{-1}$ show that the imaginary part of elastic modulus of the material $\Phi(\omega)$ weakly depends on frequency throughout this frequency interval.As soon as $H(\omega)=M\ \omega_M^2\ \omega^{-1}\ \Phi(\omega)$, we may suppose $H(\omega) \leq H(\omega_M)$ under the condition $\omega > \omega_M$.

Extrapolating the obtained results one can estimate the potential sensitivity of the gravitational wave antenna with relatively small test masses M and distances L: $M = 10^4$ g, $L=3 \cdot 10^2$ cm. Even at room temperature T=300 K its sensitivity h will be $\simeq 10^{-20}$.

It is necessary to underline one more consequence connected with the creation of long damping time $\tau_M^*$ oscillators.It is known that with the decrease of thermal bath fluctuation force acting on the test mass one obtains the situation when the sensitivity to external force is limited by the so-called standard quantum limit (SQL).The condition of achieving the SQL is the following:

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

where $\tau$ is registration time ( $\tau = 2\pi\, \omega_{gr}^{-1}$ in the case of gravitational wave detection). If $\tau = 3\cdot10^{-4}$ s, the condition (3) will be secured due to achieved value $\tau_M^* = 1.2\cdot10^7$s even at the temperature T=300 K. We should mention that the SQL cannot be considered as a ultimate limit of gravitational wave antennae sensitivity. To pass this limit it is necessary to use the appropriate procedure of measurement that differs from the simple coordinate measurement.

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