Small-vibration detector for a gravitational antenna

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There is a fundamental threshold value of the vibration amplitude of a macroscopic oscillator, at the level of $1 \cdot 10^{-17}$–$3 \cdot 10^{-18}$ cm. A highly stable microwave source with a narrow spectral line has been used in a new method for measuring vibrations. A vibration-amplitude resolution of $2 \cdot 10^{-17}$ cm has been achieved with an averaging time of 10 s.

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The intense effort being devoted to the refinement of various methods for detecting small vibrations, particularly for gravitational antennas (see the review articles by Weiss[1] and Thorne[2]), should eventually make it possible to detect vibration amplitudes $\Delta x_{\min}$ comparable to or less than the values of a fundamental significance. If, for example, $\Delta x_{\min}$ is approximately equal to the width of the wave packet of a mechanical oscillator in a coherent quantum state, $\Delta x_{\text{coh}} = \sqrt{\hbar/2m\omega_M}$ (ω_M is the resonant frequency and m is the mass), then quantum-state measurement procedures must, in principle, be used for detection in the frequency band $\Delta\omega \approx \omega_M$ (see the reviews by Caves *et al.*[3] and Braginskiĭ *et al.*[4]). For a macroscopic oscillator with $m = 10^3$ g and $\omega_M = 10^4$ rad/s, we would have $\Delta x_{\text{coh}} = 6 \times 10^{-18}$ cm. According to astrophysical predictions,[2] on the other hand, we can expect bursts of gravitational radiation of duration $\tau_{\text{gr}} \approx 10^{-3} - 10^{-4}$ s with a dimensionless amplitude $h \approx (2\text{–}3) \times 10^{-19}$. The response of a gravitational antenna of size $l = (1/2)v_s\tau_{\text{gr}} \approx 10^2$ cm to values of h at this level would be $\Delta x_{\text{gr}} \approx hl \approx (2\text{–}3) \times 10^{-17}$ cm. In this letter we outline a method for detecting small vibration amplitudes, close to these critical values.

The method makes use of one of the several devices which can parametrically convert mechanical vibrations into an electrical signal. The apparatus (Fig. 1) detects small vibrations of a niobium diaphragm D near the frequency $f_M = 8$ kHz (the lowest-frequency vibrational mode of the diaphragm has a frequency ~ 40 kHz and an effective mass ≈ 50 g). This choice of frequencies allows the detector system to filter out the thermal vibrations of the diaphragm, whose rms amplitude is $\sqrt{\overline{\Delta x_T^2}} \approx 1.4 \times 10^{-14}$ cm.

The vibration amplitude Δx is set by an electrostatic calibration system.[5] One surface of the diaphragm is part of a klystron source ($f_e = 3$ GHz). Vibration of the diaphragm causes a modulation of the capacitive part of the resonator, for which the average gap size d is 3×10^{-4} cm. This resonator, also made of niobium, has a quality factor Q_r of 5×10^4 at $T = 4.2$ K.

An external microwave sine-wave source with a frequency $f_{\text{mw}} \approx f_e$ is connected to the resonator input. The capacitance modulation leads to the appearance of side

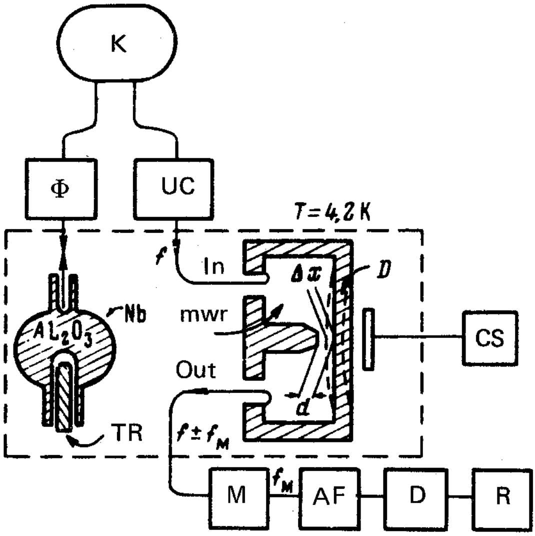

FIG. 1. Arrangement for measuring small vibrations of the diaphragm. D–Diaphragm; mwr–resonator of converter; K–klystron; Φ–phase shifter; UC–unidirectional coupler; d–capacitive gap; TR–tuning rod; M–mixer; AF–audio-frequency amplifier; D–detector; R–recorder; CS–calibration system.

frequencies $f_{mw} \pm f_e$ at the resonator output.

It is not difficult to see that the power of these side components, $(W_{out}) f_{mw} \pm f_M$, reaches a maximum at $|f_{mw} - f_e| \approx f_e/2Q_r$, and for this type of tuning the maximum power is

$$(W_{out})_{f_{mw} \pm f_M} \approx W_{in} \frac{Q_r^2}{4} \left(\frac{\Delta x}{d}\right)^2. \tag{1}$$

The necessary condition for detection, $W_{out} > kT_m \tau^{-1}$ (T_m is the noise temperature of the mixer), is satisfied for $\Delta x = 4 \times 10^{-17}$ cm at $T_m = 500$ K with $d = 3 \times 10^{-4}$ cm, $Q_r = 5 \times 10^4$ and $W_{in} = 5 \times 10^{-4}$ W if $\tau = 1$ s. In addition to this condition, the microwave source obviously must have a narrow natural and instrumental line width if low values of $(W_{out}) f_{mw} \pm f_M$ are to be measured. This requirement was one of the central problems in the development of this new method.

The microwave source is a reflex klystron stabilized by frequency pulling with a tunable superconducting sapphire resonator.[6] The stabailizing resonator, whose quality factor is $Q_{mw} = 2 \times 10^7$, is enclosed with the detector in a vacuum cryostat and held at 4.2 K. This resonator can be tuned over an interval $\Delta f_{mw} \approx 0.1 f_e$ with the help of a sapphire rod. By correctly choosing the coupling of the klystron resonator and the phase of the signal reflected from the resonator, it is possible to achieve a stabilization factor $\gtrsim 10^4$. At this value, the component of the energy spectrum, which corresponds to fluctuations of the source amplitude, does not exceed 2×10^{-18} Hz^{-1} at a detuning 8 kHz from f_{mw}, and the component in the energy

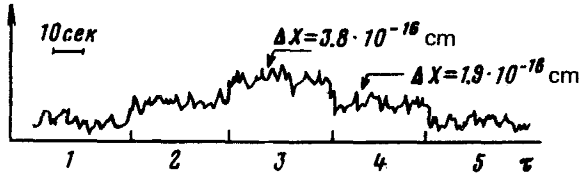

FIG. 2. Recorded response of the detector system to vibrations of the diaphragm.

spectrum corresponding to frequency fluctuations is 3×10^{-8} Hz^2/Hz (at the same detuning).

These characteristics of the microwave source, along with careful isolation of the basic parts of the apparatus from seismic and acoustic noise, have made it possible to detect small values of Δx at the level illustrated by the typical results in Fig. 2. Intervals 1 and 5 along the abscissa show the noise level, i.e., the results recorded by the system for detecting the diaphragm vibration in the absence of a calibration force. In intervals 2 and 4, a force causing a vibration amplitude $\Delta x = 1.9 \times 10^{-16}$ cm was applied to the diaphragm; in interval 3 a force causing $\Delta x = 3.8 \times 10^{-16}$ cm was applied. Statistical analysis yields $\Delta x_{min} = 6 \times 10^{-17}$ cm for $\tau = 1$ s and $\Delta x_{min} = 2 \times 10^{-17}$ cm for $\tau = 10$ s at the level of one standard deviation.

The resolution Δx_{min} achieved by this method is more than three orders of magnitude better than that of an optical detector using narrow resonances[7] or a multiple-pass Michelson interferometer.[8]

1. R. Weiss, in: Sources of Gravitational Radiation (ed. L. Smarr), Cambridge University Press, Cambridge, 1979.
2. K. S. Thorne, Rev. Mod. Phys. **52**, 285 (1980).
3. C. M. Caves *et al.*, Rev. Mod. Phys. **52**, 341 (1980).
4. V. B. Braginskiĭ, Y. I. Vorontsov, and K. S. Thorne, Science **209**, 547 (1980).
5. V. B. Braginskiĭ, V. I. Panov, V. G. Petnikov, and V. D. Popel'nyuk, Prib. Tekh. Eksp. No. 1, 234 (1977).
6. V. B. Braginskiĭ and V. I. Panov, IEEE Trans. Mag. **MAG-15**, 30 (1979).
7. S. I. Bagaev, A. S. Dychkov, and V. P. Chebotaev, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 85 (1981) [JETP Lett.
8. K. Maishchberger, A. Budiger, R. Shilling, L. Schnupp, So. Winkler, and H. Billing, Preprint, MPI-PAE/ASTRO, 209 (1979).

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