New Folder Name Pendulum Fused Silica Oscillators

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Dear Robbie,

In this envelope you will find a copy of our report N1 to you and to your colleagues about the decay time of all fuzed silica torque oscillators. It is evidently 19-th century style, but we guess that there are no other way to describe what we have done. The second copy is in our hand and, as we promissed ~~to~~ you, we shall not give it to anybody. After a short break for the summer vacation we shall continue our endeavors with the pendulum ostillators and I hope to prepare the report N2 about the decay time of this oscillators late autumn or early winter. We were confronted with some problems with the recording, but we expect to overcome them soon. All the tests we have done were made on a modest test machine. A mini-tower in the basement is still not ready. We hope that this winter we shall be able to report you news about the decay time of a one kilogram mass oscillator with longer rope (longer than one meter) from the mini-tower testing machine.

Thank you for the copy of your article in Science about LIGO. I have to remark here that we have a <u>friendly</u> disagreement: you mentioned on the page 330 that the quality factor with <u>one ton</u> must be 10^9, from my point of view this is <u>not</u> possible due to the losses in the support system.

I take the liberty to add to the report a copy of
a short article in SOV. PHYS. JETP which has no know-how
information and a review report for the symposium
„Quantum Physics and the Universe". You will not find anyth-
new in the review report expept perhaps some remarks about
the importance of the excess noise. If somebody will read
this review, I am sure, he will decide that ~~that~~ the author
is a pro-LIGO lobbist. And his decision will be correct one

with cordial regards

yours Vladimir.

August 5. P.S. I am happy to add that we successfully
tested in a new version the decay time of
the <u>pendulum oscillations</u> (the type of the oscillator
was the same, but the readout system was a new
one). After 3 days of continuous record we may
say that this oscillator <u>has the same</u> decay time:
approximately $1 \cdot 10^{+7}$ sec ($\pm 30\%$). We have not yet
used anealing procedure, which is essential. We intend
to test several oscillators this automn and then
we shall send you the report N2.
I want also to thank you: the laser printer arrive
and it is in working condition! The tenacity of
the purchasing division of Caltech is remarcable!

yours Vladimir

REPORT (No. 2)

PENDULUM FUSED SILICA OSCILLATORS WITH SMALL DISSIPATION

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This report is the second part of the energy dissipation investigation in oscillators of fused silica. The decay time of pendulum oscillations of such oscillators is longer than 4×10^7 s and corresponds to the quality factor $> 1.3\times10^8$.

The content :

1. The design of the oscillators and the test installation.

To investigate the decay time of pendulum swing of the all-fused silica oscillators we used the oscillators fabricated as it was described at the Report No.1. The silica cylinder (with mass m=30 g) was suspended on a thin silica thread (the radii of threads were r = 60-100 μm, the lengths - l = 28-32 cm). The eigen frequency of pendulum oscillations were near $\omega_m \simeq 5\ s^{-1}$.

The employed technique of thread preparation, its welding to cylinder and to the upper slab was identical that for the preparation of the torsion oscillators.

Here it is pertinent to emphasize the basic requirements of high-quality oscillators preparation. They are :

a) Quartz with the lowest impurity content is used.

b) The quartz thread is welded to the cylinder and to the upper slab to avoid the additional losses of energy if the clamping of thread was used.

c) Just before the thread manufacturing the surface of quartz stick was thoroughly cleaned.

d) The upper slab must be as massive as possible.

The decay time measurements of the pendulum oscillations were carried out in the same vacuum chamber as the torsion ones after the setting of additional device for registration of pendulum swing amplitude. By this means the installation permits to study both pendulum and torsion modes of the oscillators.

The scheme of the decay time measurements of the pendulum oscillations is shown on Fig.1. The oscillations were excited by means of special manipulator (6) installed inside the vacuum chamber (1). The measurements of the projection of pendulum amplitude on two mutually normal planes were carried out because it was necessary to record the change of the total mechanical energy.

The oscillations were registered by an optical meter. It provided the minimal influence of registration system on the tested oscillator. The beams of two He-Ne (2) lasers passed through the beam-splitters (3) and formed two couples of parallel beams. The distance between the beams in the couples was slightly larger than the diameter of the pendulum cylinder D (4). The couples of the beams were perpendicular one to another. The beams hit two pares of slits 1 mm wide. The photodetectors (5) were situated behind the slits. If the amplitude A of pendulum oscillations was within limits

$$(b - D)/2 < A < (b + D)/2$$

where b is the distance between the edges of slits, the oscillating cylinder at first opened one slit and then closed another. We measured by a frequency control meter the interval τ between these two events. If in its equilibrium position the cylinder was symmetric relatively the slits, then the amplitude of oscillations depends on τ as follows :

$$A = \frac{b - D}{2 \sin \omega\tau/2} \quad . \qquad (1)$$

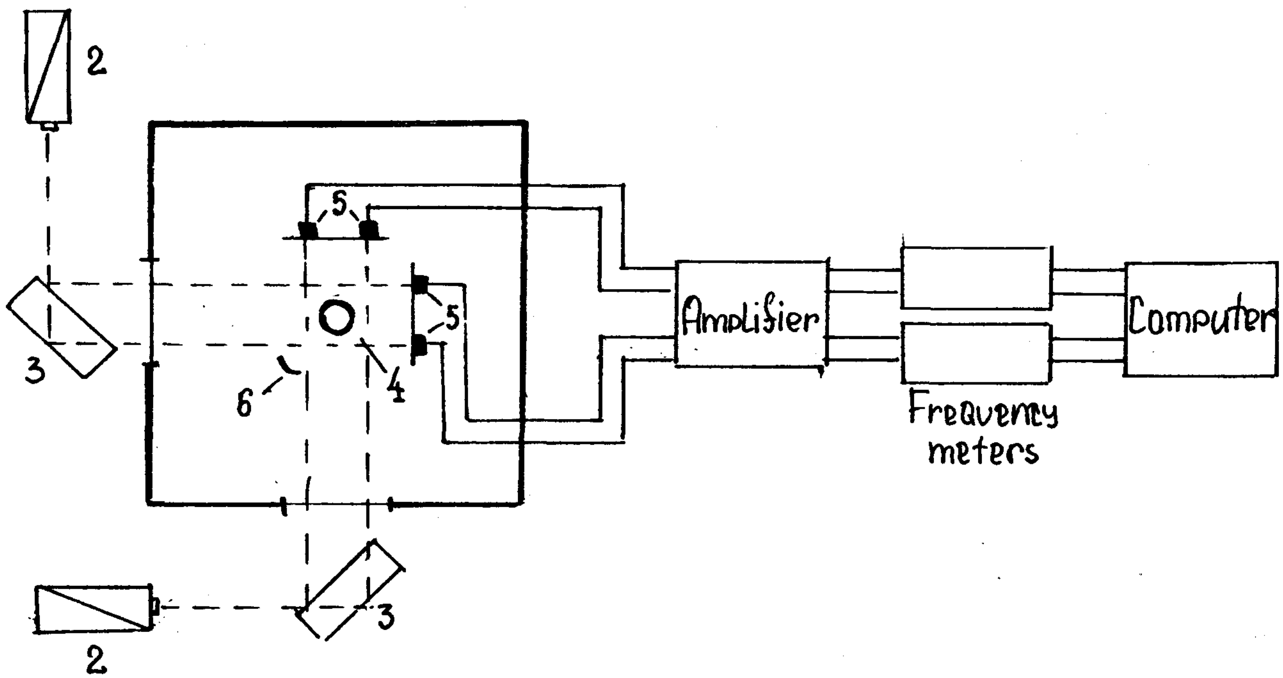

Fig.1 The scheme of the experimental installation.

Substituting (1) in formula $\tau^* = - \frac{A}{dA/dt}$ one obtains the expression for the decay time

$$\tau^* = \frac{tg\ \omega\tau/2}{\omega/2} \quad \frac{d\tau}{dt} . \qquad (2)$$

For the high-quality oscillators ($t_{meas} \ll \tau^*$) over the time of measurement t_{meas} the variation of interval $\Delta\tau \ll \tau$, hence the time dependence of magnitude τ can be approximated by the linear model, its slope defines the decay time τ^*.

2. The relation between the oscillator decay time and the energy dissipation in the material.

The decay of pendulum swing of oscillator is not directly related to magnitude of the imaginary part of the elastic modulus, as in torsion oscillation. The suggestion that the quality factor of pendulum Q_m will be [1]

$$Q_m \simeq Q_{int}\ 2\ l \left(\frac{m\ g}{J\ Y} \right)^{1/2} \qquad (3)$$

(Q_{int} is the intrinsic losses in material of the thread, J - the moment of inertia of cross section of the thread, Y - the Young's modulus) was reasonably good supported for the materials with relatively large Q^{-1}_{int}. We manufactured the oscillator of alkale-silica glass with the geometrical parameters similar to the quartz oscillators ones, following the analogous technique. The alkale-silica glass is characterized by the high level of intrinsic losses and the observed value of Q_m^{-1} for this oscillator was wholly determined by the losses in material. For the torsion mode (ω_{tors}=1.3 s^{-1}) the quality factor Q_{tors} was 1×10^3, for the pendulum mode (ω_{pen} = 5.5 s^{-1}) - Q_{pen} = 7.5×10^4. This result is in agreement with formula (3).

Nevertheless, the estimations of the quality factor of pendulums by means of the torsion experiments results calls for the particular attention especially for the high quality oscillators. Due to the distinctions between pendulum and torsion decay mechanisms the losses can vary in level for these two types of oscillations.

- So one must take into account the thermoelastic losses, which occurs only for pendulum oscillations. The estimation of the level of thermoelastic losses calls for the additional calculations, because the upper part of the thread that experiences the highest deformations has variable cross section.

- During the pendulum oscillations part of the energy dissipates due to the periodical extending of the thread.

- The repumping of energy from one pendulum mode to another (this effect will be described below) may play the significant role in energy losses in high quality oscillators. For the precise theoretical estimation of this process one needs an adequate model of this process.

Thus only the direct measurement of the decay time of pendulum oscillations may give a reliable information about the losses.

3. The special features of experiments with pendulum modes of high quality oscillators.

Fig.2,3 show the samples of time dependence of the pendulum amplitude projections onto two mutually normal planes. Fig.2 corresponds to the large amplitude of oscillations, Fig.3 - to the relatively small one. This is the typical picture of beats when energy transmits from one mode to another with the small dissipation of the total energy of pendulum.

The asymmetry of oscillator and the elastic spring constant of the thread causes the existence of two pendulum modes, characterizing by the different frequencies. So the pendulum oscillations are the beats between these two modes with frequency $\Delta\omega_{asym} \simeq (3\text{-}10)\times10^{-4}\ s^{-1}$.

Besides, the action of Coriolis force usually results in the rotation of the plane of pendulum oscillations with frequency $\Delta\omega_{Cor} = \Omega_{Earth} \sin\varphi$ (Ω_{Earth} is the frequency of the Earth rotation, φ - the latitude of the place, where the pendulum is situated). It causes the addition split of modes of pendulum oscillations [2].

It is also necessary to take into account the nonlinearity of pendulum oscillations, which results in dependence of modes frequencies on the amplitude of oscillations: $(\Delta\omega/\omega_p)_{nl} \simeq A^2/16$ [3]. If $A \gtrsim 3\times10^{-2}$ rad the variance of frequencies due to the pendulum nonlinearity is comparable to its split due to asymmetry. In this case picture of modes beats becomes more complicated. The corresponding time dependence of amplitude projections looks like shown on Fig.2.

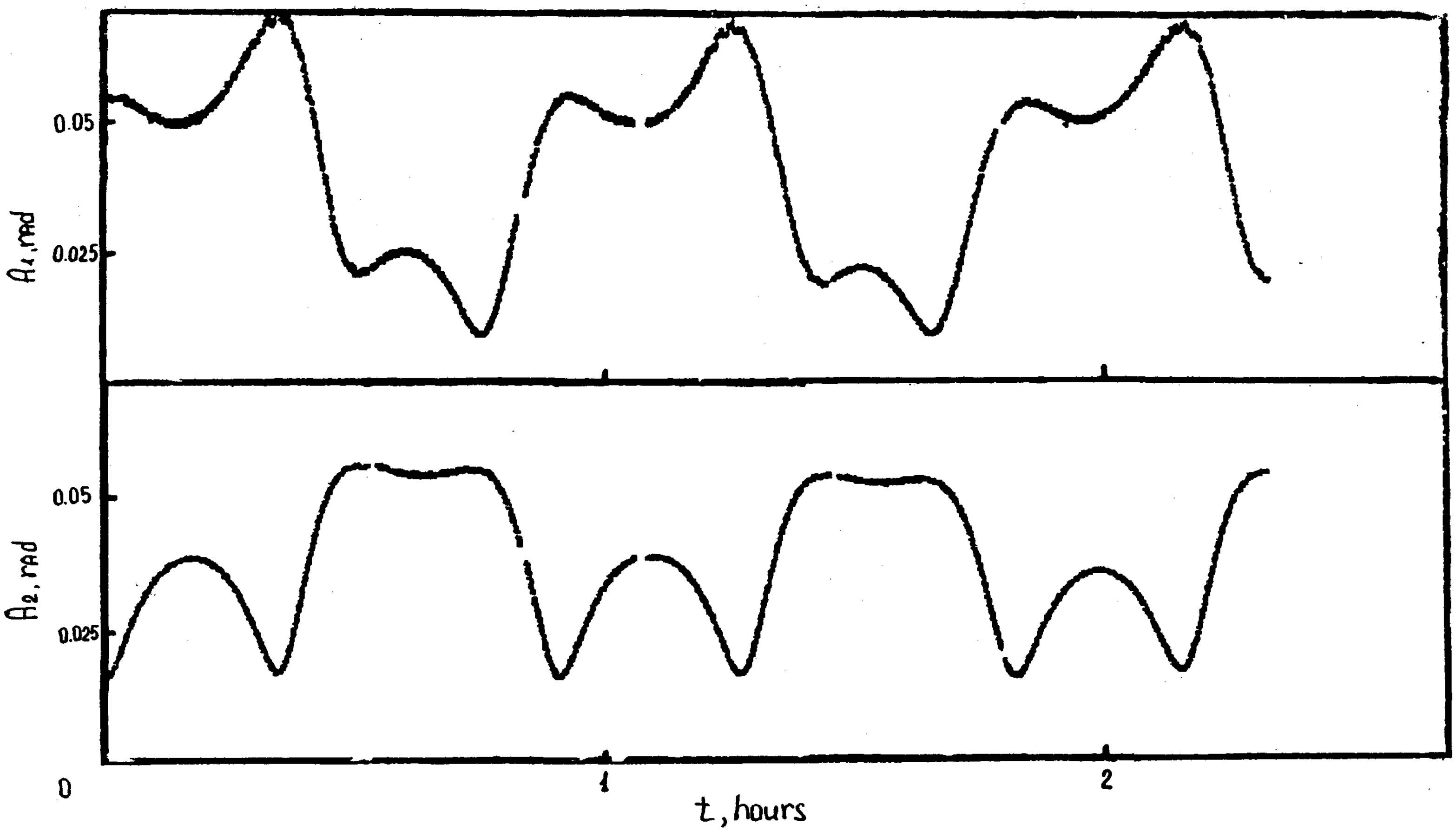

Fig.2 The time dependence of two projections of the pendulum amplitude (the large amplitude).

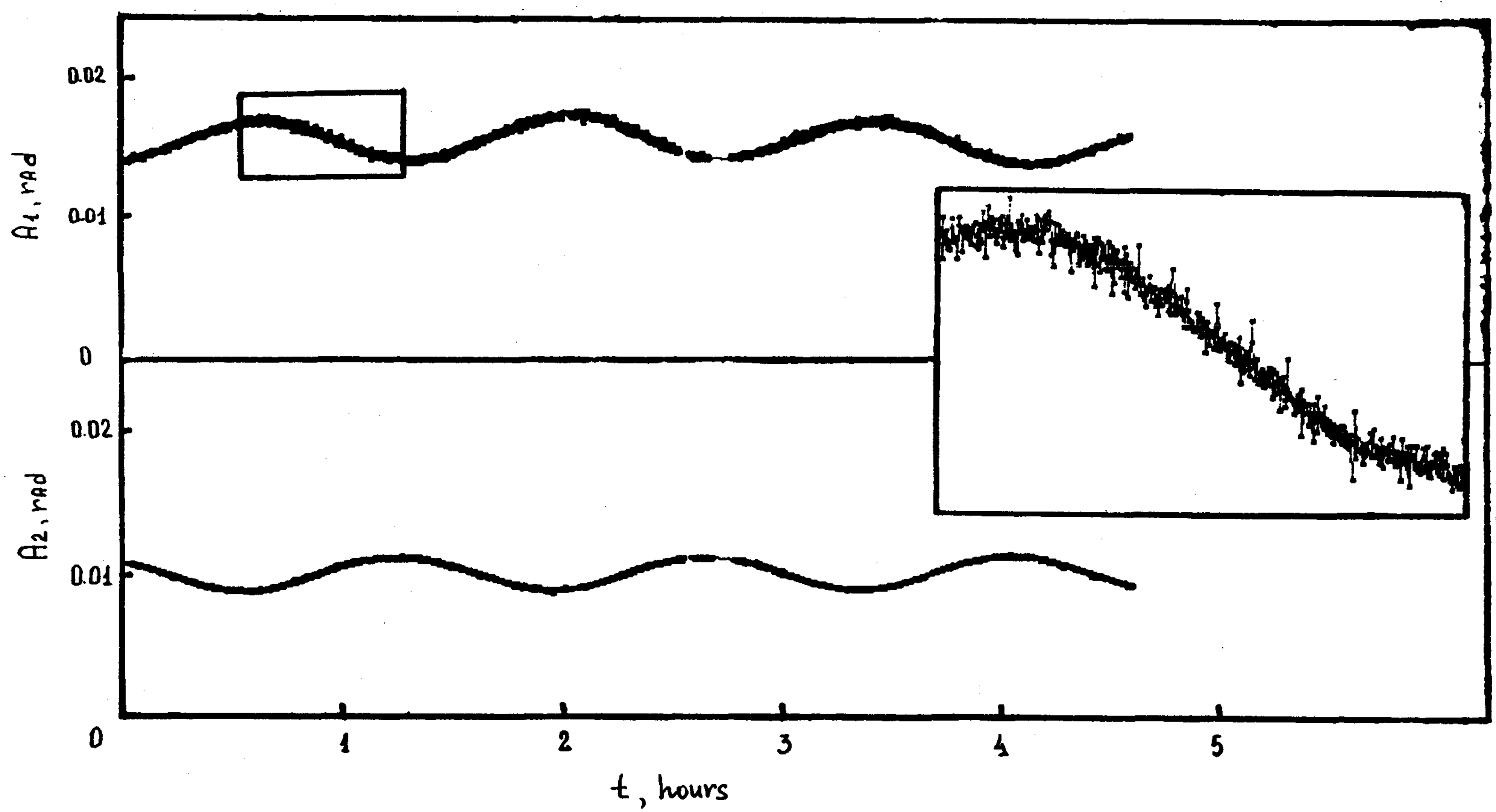

Fig.3 The time dependence of two projections of the pendulum amplitude (the small amplitude).

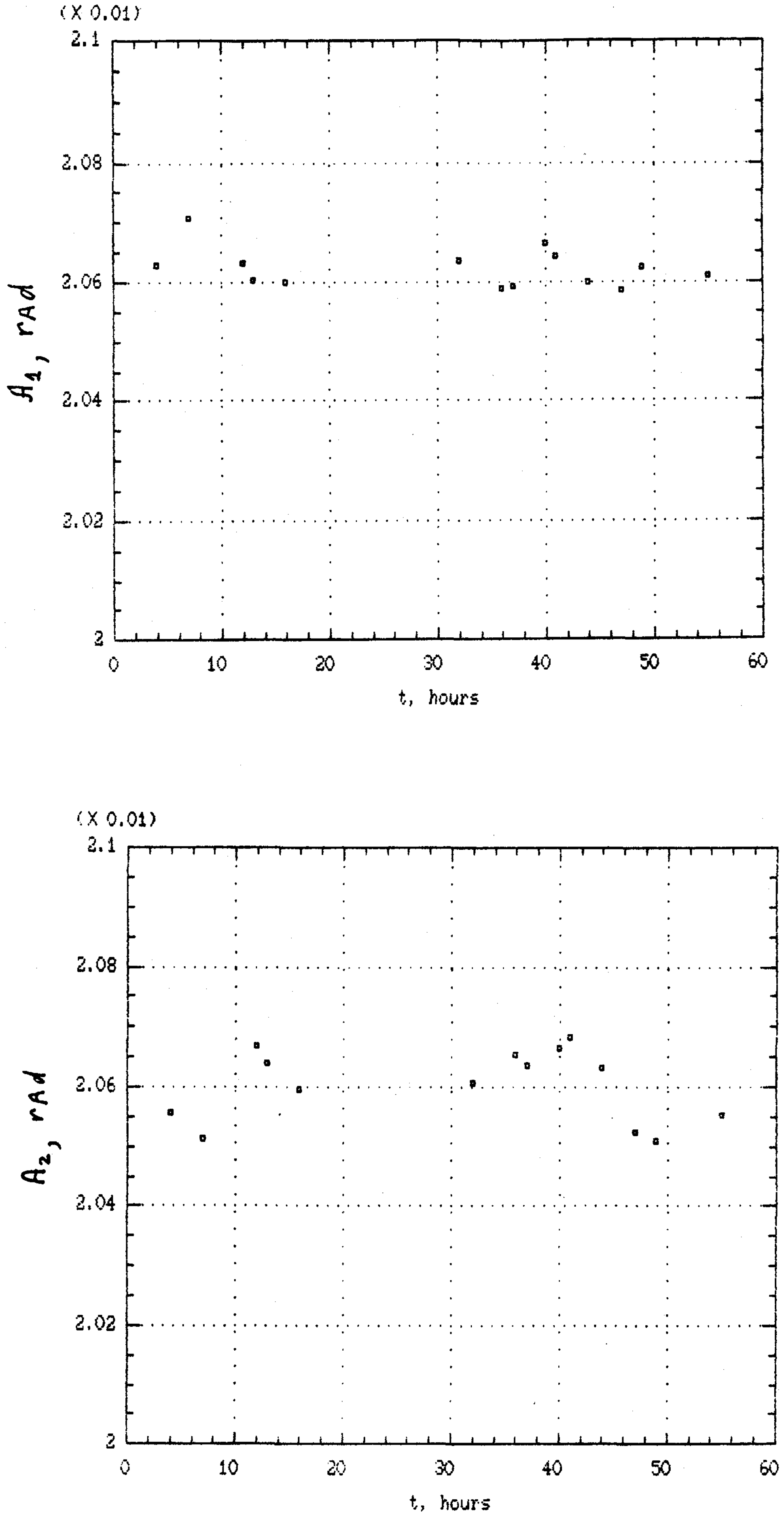

Fig.4 The time dependence of two projections of the pendulum amplitude over the time period 60 hours.

5. Conclusion.

Our investigations show, that the developed technique of fabricating the test masses and the suspension permits to reach small dissipation of energy for the pendulum oscillations. Its relaxation time is longer than 4×10^7 s. The additional investigations are necessary to turn to full size prototype test masses with seismic vibration isolation system and to evade the additional channels of energy dissipation in this case.

References:

1. P.R.Saulson, Phys. Rev. D42, (1990), 2437.
2. A.B.Pippard, The physics of vibration, Cambridge Univ. Press, Cambridge, 1985.
3. V.V.Migulin, V.I.Medvedev, E.R.Mustel, V.N.Parigin, Theory of vibrations, Moscow, 1980.

The amplitude of the beats between two modes of the pendulum depends on the direction of its excitation relative to its main axes. To decrease the systematical errors of relaxation time calculation from the experimental amplitude variations we chose the most favorable operation conditions of a small beats amplitude. The conditions were determined by experimental searching of the appropriate direction of the initial pendulum deflection from the vertical. This regime is shown on Fig.3. There is the slight beats between modes of oscillations with frequency $\Delta\omega_{asym}$ ($\Delta\omega_{asym} > \Delta\omega_{nl} > \Delta\omega_{Cor}$) and amplitude $A \leqslant 3 \times 10^{-2}$ rad. The beats period was near one hour and we did not increased it specially, although the technique permitted to manufacture much more symmetric pendulums.

So the pendulum oscillations of the mass suspended on one thread are rather complicated. Nevertheless we began the investigations of the energy dissipation for such type of oscillators for the following reasons: 1) this permits investigate simultaneously the material losses (torsion oscillations) and the pendulum losses; 2) for the pendulum suspended on two or more threads the coupling mode effects may be significantly weaker, but this configuration may give the additional channel of dissipation.

4. The results of the experiment.

Fig. 4 presents the time dependence of two projections of amplitude in one of the tested oscillators recorded over the time period 60 hours. The microseismic action on the pendulum was the main source of amplitude fluctuations and thus it defined the accuracy of decay time measurement. As it was mentioned above, we did not increase the amplitude in order to avoid the influence of nonlinearity, although this could permit to decrease the relative level of fluctuations. We also did not use any damping of seismic disturbances because this could give the additional losses in tested oscillators. During several days of observations we did not distinguish a significant decrease of the amplitude. The regression analysis of the record permitted to obtain with confidence level 0.95 that the decay time was

$$\tau_m^* \gtrsim 4.4 \times 10^7 \text{ s}$$

and correspondingly $Q_m \gtrsim 1.3 \times 10^8$ for the eigen frequency $\omega_m = 5.5 \text{ s}^{-1}$.

Unfortunately we could not increase the accuracy of measurements increasing the time of observation, because after ~ 100 hours of continuous work the discharge vacuum pump began to exhaust gases into chamber. The first 30-40 hours after the pumping of operating volume and excitation of oscillations we did not used for measurements because the transition processes took place at that time.