New Folder Name Torque 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 you, we shall not give it to anybody. After a short break for the summer vacation we shall continue our endeavors with the pendulum oscillators 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 acticle in Science about LIGO. I have to remark here that we have a _friendly_ disagreement: you mentioned on the page 330 that the quality factor with _one_ _ton_ must be 10^9, from my point of view this is _not_ 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 expt 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 autho 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 pendulum oscillations (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 has the same decay time: approximately $1 \cdot 10^{+7}$ sec (± 30%). We have not yet used anealing procedure, which is essential. We inten 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

Kip's Copy
LIGO-T930020-00-R

REPORT (No. 1)

TORQUE FUSED SILICA OSCILLATORS WITH SMALL DISSIPATION
(the technology of preparation and methods of measurements)

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In this paper the technology of all-fused silica oscillators preparation is presented. This technology permits to achieve the decay time of oscillators $\tau_M^* = (1.2 \pm 0.1)\cdot 10^7$ sec and the quality factor $Q_M \simeq 7\cdot 10^6$.

The content:

1. The design of the oscillators and the technology of preparation.

To test the decay time of torque oscillators made of fused silica we chose the following simple form of the oscillators: a quartz cylinder was suspended on a thin quartz thread. In the series of tests we used cylinders with the relatively small mass $m = 30$ g (the moment of inertia $I \simeq 25\ g\cdot cm^2$). The radii of quartz threads were $r = 60-100\ \mu m$. The eigen frequencies of tested oscillators were $\omega_M = 1-5\ sec^{-1}$.

The quartz thread of the oscillators was prepared in the following way: a quartz stick with length 2.5-3 cm and diameter 0.2 cm was preliminary cleaned with chemicals to remove from the surface the organic and anorganic impurities which may cause the additional losses of energy in oscillator. Thus the stick was placed for 30 minutes in the mixture of chromic and sulphuric acids (to remove the organic impurities) and then for 30 minutes in the 15% solution of hydrofluoric acid (to remove about 10 μm of fused quartz surface layer). After this the surface of the stick was carefully washed in distilled water. Then the prepared stick was situated in the open flame of oxygen burner to heat the middle of the stick up to the temperature $T \simeq 1400^oC$ when quartz became soft. The volume to be heated depends on the required length and thickness of the thread, it must be approximately 10 times the volume of the thread. Thus to prepare the thread with the radius 100 μm and length 30 cm it is necessary to heat approximately 0.5 cm of the stick with diameter 0.2 cm. The softened quartz was lengthened out manually to receive the thread with two short sticks on the ends (see Fig.1). A microscope was used to measure the diameter of the thread. The irregularity of the thread radius as a rule did not exceed $\Delta r/r = 0.2$.

The choice of the fused silica kind for the stick preparation was the important point of the work. It is well known that the fused quartz usually has several types of impurities (NaOH, KOH, $CaCO_2$, attached water, etc.). These impurities not only affect the window of optical transparency but also affect the mechanical quality factor. To prepare the stick we chose quartz which had had at high mechanical frequences ($\omega_M = 6 \cdot 10^3 sec^{-1}$) the high quality factor ($Q_M \geq 10^7$). This kind of fused quartz had been tested in another laboratory by measuring the Q_M of a tuning fork type mechanical oscillator [1].

The next step was the attaching of the thread to the cylinder and to the upper support (a massive block of fused quartz). To avoid additional losses we did not use any bolts to attach the thread to the cylinder and to the quartz block: the short sticks at the ends of the thread were welded to the cylinder and to the block. The cylindrical juts in the welding areas of the block and the cylinder were shaped by diamond tools as shown at Fig.1 to decrease the temperature gradients during welding which can cause the residual gradients of tension (an additional source of losses) The stick at the end of the thread and the jut were brought close together and heated in the flame of oxygen burner up to $\simeq 1800^oC$. In the case of visible optical unhomogenities absence after getting cold we estimated the quality of welding as good.

After realization of all this procedures the prepared oscillator was installed without delay in vacuum chamber. It was necessary to avoid the accumulation of the oil, water and dust on the surface of the thread.

2. The design of the test installation.

The scheme of the test installation is shown on Fig.2. The mechanical part consisted of two heavy brass discs (each disc had the mass $\simeq 5 \cdot 10^3$g). The lower disc was attached to the bottom of the vacuum chamber. The discs were joined by three brass columns. The quartz block was situated on the top disc. We used the heaviest available in the lab discs and the block to reduce the dissipation in the support system. It is possible to show that the losses in the support system limit the quality factor of the oscillator according to the simple formula:

$$Q_{osc}^{-1} \simeq Q_{supp}^{-1} \frac{J_{cyl}}{J_{supp}} \left[\frac{\omega_M}{\omega_{supp}} \right]^3 \qquad (1)$$

where Q_{supp} is the quality factor of the lowest torque mode of the support which has the eigen frequency $\omega_{supp} \gg \omega_M$, J_{supp} is the moment of inertia of the top disc with the quartz block, J_{cyl} is the moment of inertia of the test cylinder which with the quartz thread constitute the oscillator. In our measurements $Q_{osc} \simeq 1 \cdot 10^4 \cdot (10^2)^3 \simeq 10^{10}$. This value is several orders higher than the measured magnitude $Q \simeq 10^6 - 10^7$ that may be regarded as the intrinsic one thus the losses in the support may be neglected. On the other hand the parameters of our installation (ω_{supp} and J_{supp}) do not permit us to test heavier oscillator and be sure that the effect of "support limiting" Q_{osc} is negligible.

The presence of slightest quantities of oil vapour on the thread surface can seriously decrease the quality factor. To pump out the chamber with the installation we used a ceolit pump (till $8\cdot10^{-3}$ torr) and then the working vacuum ($2\cdot10^{-6}$ torr) we obtained with the help of magneto discharge pump.

To be able to heat the thread of the oscillator *in situ* (this turned out to be the essential part of procedure) a heater was installed inside the apparatus. It consisted of heated with tungsten wire stainless tube that surrounded the quartz thread and a couple of coaxial screens. To control the temperature inside the heater we used a copper-constantan thermocouple.After the calibration procedure (determination of temperature dependence on heating current) the thermometer was removed to avoid the possible additional source of losses. The heater permitted to warm the thread up to $T = 500\ ^oC$.

3. The method of the decay time measurements.

We chose a simple way of the oscillator excitation based on the use of pondermotive electrostatic force. The bottom of the cylinder was partly covered with graphite (two sectors electrically coupled). Two metallic plates which had the same form as the sectors were situated under the main cylinder. These plates had an angular shift relatively the sectors. The gap between the bottom of the cylinder and the plates was 0.15 cm. Applying a d.c. voltage $U \simeq 1000$ V between the plates it was possible to produce oscillator angular shift $\simeq 3\cdot10^{-3}$rad if $\omega_M \simeq 1\ \mathrm{sec}^{-1}$. Usually we applied several d.c.pulses to the plates with the period close to $2\pi/\omega_M$. It was sufficient to excite the torque oscillations with the angular amplitude (1-5)$\cdot10^{-2}$ rad.

The probable source of dissipation associated with this system of excitation is electrostatic charge on the surface of the cylinder. Estimations, which we omit here, shows that this probable source corresponds the decay time $\tau_M^* \geqslant 10^{10}$ sec.

The decay time τ_M^* was measured by registering the change of the free oscillations amplitudes when the system of excitation was switched off. The oscillations were registered by an optical angular meter: the optical beam reflected from the mirror, attached to the oscillator cylinder, reached the net of detectors situated on a panel. When the light spot passed the photo detectors the electrical pulses were generated. The intervals of time, which depended on the angular amplitude of oscillations, were registered by a frequency control meter and then recorded. This system of measurements permitted to accumulate data during several days (this is the typical time of one measurement). The scheme of the installation for the decay time measurement is shown on Fig.2.

If the laser beam passes between two photo detectors during the time interval $\Delta\tau$, the following relationship is true:

$$A = \frac{\Delta X}{L \operatorname{Sin}(\Delta\tau\, \omega_M)} \qquad (2)$$

where ΔX is the distance between photo detectors, A - the amplitude of the torque oscillations, L - the path of the beam from the mirror on oscillator to photo detector.

As far as decay time is defined

$$\tau_M^* = - \frac{A}{dA/dt} \qquad (3)$$

one can obtain the simple relationship between τ_M^* and the change of the time interval $\Delta\tau$ in the course of time t (under the conditions: $\Delta\tau\ \omega_M \ll 1$; $t_2 - t_1 = T \ll \tau_M^*$ where T is the time of observation)

$$\tau_M^* \simeq \frac{(t_2-t_1)\ \Delta\tau_1}{\Delta\tau_1 - \Delta\tau_2} . \qquad (4)$$

Hence experimentally measured interval $\Delta\tau$ linearly depends on the observation time T . Using the linear regression analysis we calculate the decay time.

Evidently the accuracy of the measurement method is determined by the variance of time interval of laser beam passing between the photo detectors. Fluctuations of this value are caused by laser power changes, trigger level variations of the frequency meter counters and so on. But the main source of fluctuations is the seismic excitation of nontorque oscillations of the quartz cylinder suspended on the thread, namely modes M_1 and M_2 - pendulum oscillations in two mutually orthogonal directions, M_3 and M_4 - the rotations of the cylinder around two orthogonal horizontal axes,passing through the cylinder center of mass. In steady state the average amplitude of oscillations of this modes depends on their quality factors and the magnitude of the oscillator suspension point seismic motion. Since we did not used any seismic vibration isolation system and these modes had high quality factors $Q > 10^6$, the average amplitude of modes M_1 and M_2 achieved $5 \cdot 10^{-2}$ cm, modes M_3 and M_4 - $5 \cdot 10^{-3}$ rad. These oscillations caused motion of the reflected laser beam in horizontal and vertical direction and shift of the time point at which the photo detectors were triggered. The RMS of a relative error of the time interval duration $\sigma(\Delta\tau)/\Delta\tau$ was near 10^{-3}. It permitted to measure $\tau^* \simeq 10^7$ s per time less then 10^5 s with the accuracy near 10%.

Nevertheless a procedure of the oscillator decay time measurement usually takes several days. One of the reasons is that we can not monitor the true amplitude of the oscillator immediately after pumping the chamber to high vacuum and exciting of torque oscillations. Representative time dependence of the time interval ΔT recorded at the beginning of measurements is shown on Fig.3. It imitates light increasing of the oscillator amplitude. This fact can be explained if one takes into account that measured value $X(t)$ is the sum of the harmonic oscillations $S(t)$ and noise oscillation $N(t)$ produced by seismic vibration that we consider as Gaussian noise.

$$X(t) = S(t) + N(t) \qquad (5)$$

The total signal amplitude $\rho(t)$ statistical distribution is the generalized Rayleigh distribution [2]:

$$W(\rho) = \frac{\rho}{\sigma^2} I_0 \left[\frac{\rho \rho_s}{\sigma^2} \right] \exp \left[- \frac{\rho^2 + \rho_s^2}{2 \sigma^2} \right] \qquad (6)$$

where I_0 is modificated Bessel function, σ^2 is variance of noise,

$$X(t) = \rho(t) \cos [\omega_M t + \phi(t)],$$

$$S(T) = \rho_s(t) \cos [\omega_M t + \phi_s(t)].$$

So the measured amplitude

$$\bar{\rho}(t) = \int_{-\infty}^{\infty} \rho \, W(\rho) \, d\rho \qquad (7)$$

can change its value due to variation of σ^2 which is caused by seismic exciting of all oscillator modes:

$$\bar{\rho}(t) \simeq 4\,\rho_s\left[\frac{1}{4}+\frac{\sigma^2}{2\,\rho_s}\right] \qquad (8)$$

under the condition $\rho_s/2\,\sigma^2 \gg 1$.

After the lapse of time necessary to establish steady-state amplitudes of oscillations in modes $M_1 - M_4$, corresponding to the middle level of the seismic noise in laboratory (this time was near 10^5 s) we registered linear dependence of interval $\Delta\tau$ duration on time and founded the magnitude of the decay time τ^*_M by the least-square method.

4. The results of measurements.

Eight fused silica torque oscillators were fabricated accordingly to the described above technology and tested.

The decay time of this oscillators tested without heating in vacuum after preparation was $(2\text{-}4)\cdot 10^6$ s (frequency $\omega_M = (1.1\text{-}1.6)\ s^{-1}$. If the threads of oscillators had been heated at 300-350^{0}C during 3-5 hours and then cooled straight before the measuring the τ^*_M value increased.

The maximum achieved magnitude is

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

that corresponds $Q_M \simeq 7\cdot 10^6$. Fig.3 shows the experimental time dependence of $\Delta\tau$. The regression analysis of the part of this curve,measured after the completion of transitional processes, reveals the τ^*_M magnitude.

After the oscillator stay in low vacuum (10^{-1} tor) during 10-12 hours the τ^*_M value decreased but the repeated heating restored it.

The obvious dependence of τ_M^* on the circumstances of heating shows that the τ_M^* value $(5\cdot10^6-10^7)$ s characterizes the damping processes connected with thread surface phenomena. Since the structure changes in fused silica take place at the temperatures above 600°C, heating at 350°C evidently affects desorbtion of absorbed molecules, specifically water vapor, from the thread surface and diminution of the viscous loss on the surface. On the way of surface damping processes elimination apparently the further τ_M^* and Q_M increasing is possible, until the value of Q_M will be limited by the loss in fused quartz structure.

5. Conclusion.

1. The achieved value of quality factor Q_M for torque fused silica oscillators is the highest on record for low frequency mechanical oscillators. But it is not to be considered as a limit of a fundamental nature. It can be increased, for example, by more careful cleaning of quartz thread surface. For the same energy dissipation Q_M^{-1} τ_M^* can be increased with l (the length of the thread) and J (moment of inertia of mass) increasing.

2. All measurements were performed on the preliminary test installation. The advanced installation which we are creating now will permit to test oscillators large masses and lengths of the threads. We project to measure τ_M^* and Q_M for pendulum fused quartz oscillators as well.

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REFERENCES

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2. S.A.Akhmanov, Ju.E.Djakov, A.S.Chirkin, Introduction to statistical radiophysics, Moscow, Science, 1981.

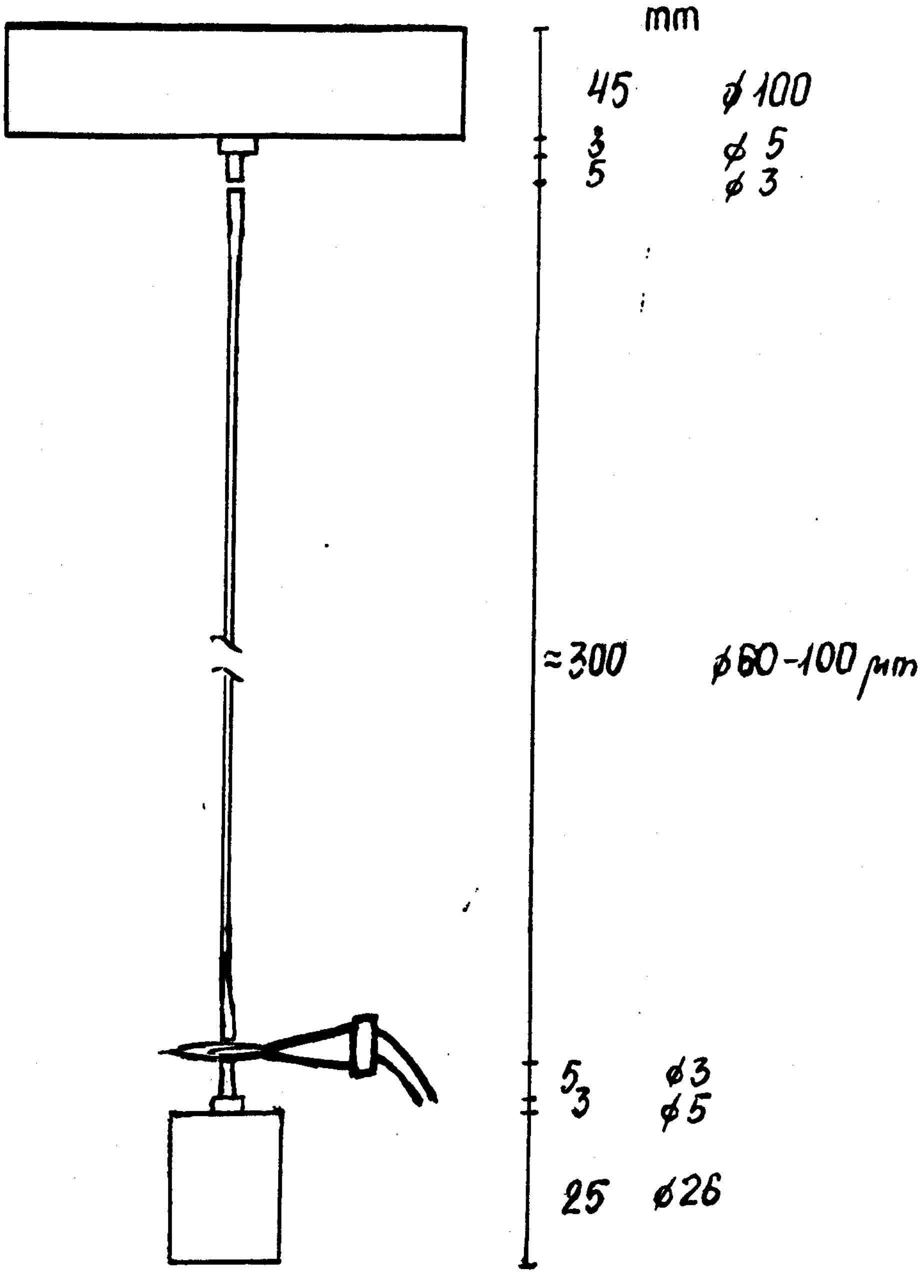

Fig.1. Design of the fused quartz torque oscillator.

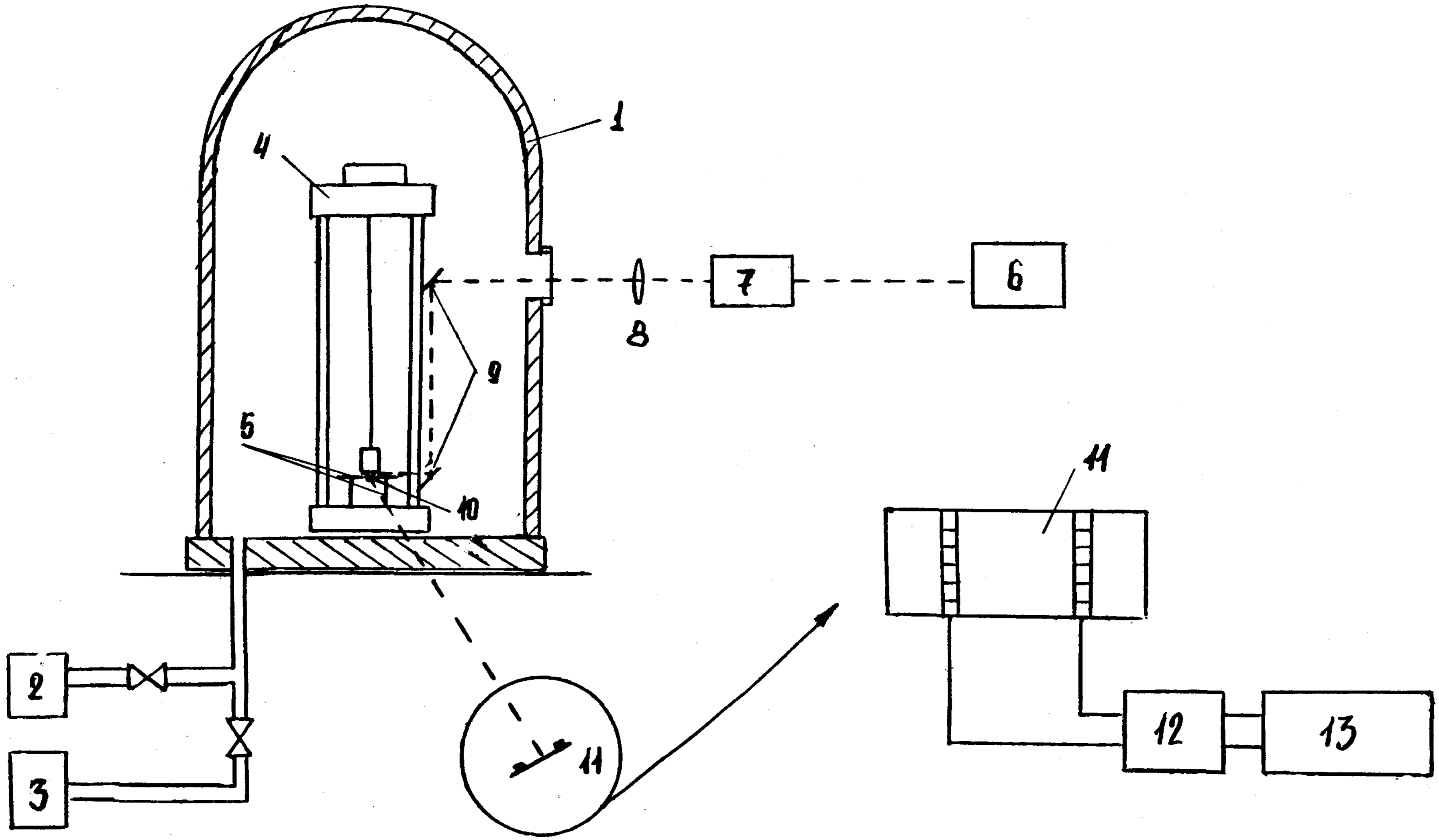

Fig.2.Scheme of the test installation: 1-vacuum chamber; 2-ceolit vacuum pump; 3-magneto charge vacuum pump; 4-top disc; 5-two metallic plates; 6- He-Ne laser; 7-beam collimator ; 8-long focus lens ; 9-mirrors; 10-mirror attached to cylinder; 11-photo detector panel; 12-formative amplifier; 13-frequency meter.

Fig.3. Dependence of Δτ vs time.