Paraconic Pendulum as precise Tiltmeter

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1. Introduction

High precision tilt measurements are necessary to solve a lot of problems in science, engineering, building, and so on. There are different kinds of tiltmeters to measure small tilts (amplitude till 0.05 arcsecond) of investigated objects: hydrostatic tiltmeter, which has a water as sensitive element; pendulum tiltmeters where the sensitive element is a pendulum suspended by thin metal thread, and others.

We experimented a possibility to use the paraconic pendulum device as tiltmeter. The sensitive element of such device is a paraconic pendulum – solid metal body with quartz rod and metal stirrup suspended to support plate by a small ball or knife free to roll on a horizontal support plate (Fig. 3); it has a minimal temperature coefficient, and a rigid structure.

The aim of our investigation is the registration by our device of small tilts of different kinds of objects (buildings, pedestals, bases and so on) <u>*in the range of tidal tilts of Earth surface*</u>*. The investigation of tiltmeters the range of tidal tilts of Earth surface is not a trivial problem because it is necessary* <u>*to preset a smooth sinusoidal signal with a very small amplitude – till 0.05 arcsecond.*</u>

The device was put on a horizontal tilting table, which can preset the angles of tilt in the range of tidal tilts of Earth surface, so we got the inclination of pendulum body relatively to its frame. To have a smooth tilting of our table in such small interval we use the Verbaandert bearing ("crapaudine") on which one of three plate feet was put. It's a metal cylinder with a thin upper wall (Fig.1, Melchior 1966).

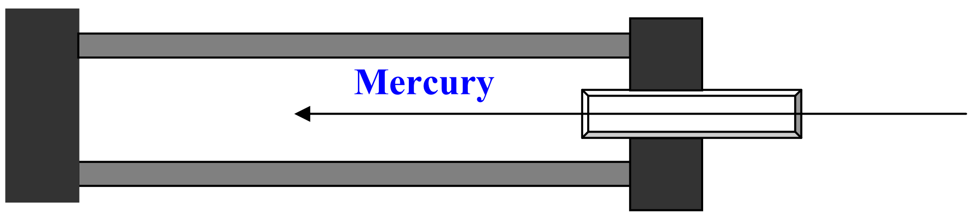

Figure 1: Principle of the Verbaandert bearing (inflatable "crapaudine")

The cylinder is connected through a plastic pipe with a vessel fastened on a rotating arm (Fig.2).

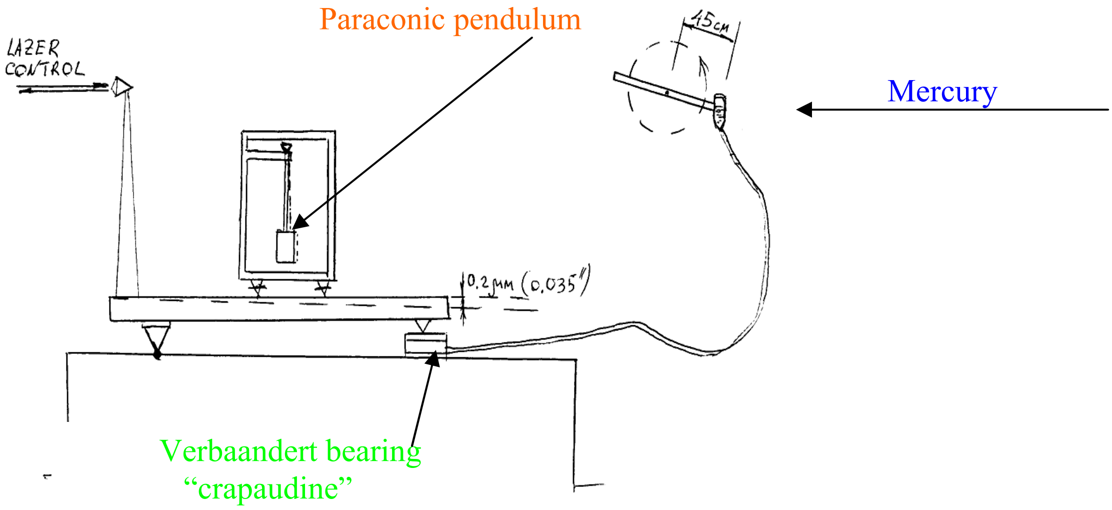

Figure 2: Principle of the tilting table

The vessel, pipe, and crapaudine are filled with mercury. The mercury in vessel communicates with the atmosphere. The change of the mercury pressure in the cylinder, produced by the rotation of the arm, deforms the upper wall as diaphragm. It bends till 100 nanometer, and lifts (or lowers) the foot of the tilting table. Fastening the mercury vessel in various positions on the arm we can modify the amplitude of the mercury pressure variations in the crapaudine and consequently the amplitude of tilt of the table. We chose a period of rotation of the arm equal to 15 min.

The motion of pendulum was registered by the capacitive displacement transducer (Nanoukin and Rebrov, 1982). It can register the change of distance between the pendulum lower body and the plates of measuring capacitor with resolution 10^{-10} m during 1 min in the range of 27 arcsecond. There are 4 plates fixed around the lower pendulum body in distance 0.5 mm to register the horizontal pendulum motion in two perpendicular planes (Fig.3).

We controlled the smooth rotation of the arm, the regular tilt of the table and the quality of the capacitive transducer by Michelson phototachymeter: a rod with a corner reflector was fixed on the tilting table. The angle of tilt of the base plate measured by interferometer was (0.035 ± 0.003)″; the lower pendulum body displaced correspondingly of 40 nanometer.
Before experiment the capacitive displacement transducer was calibrated by static method with the device of horizontal displacements. To evaluate the investigated signal and noises we used the capacitive plates of the same area that for the experiment ($6cm^2$).

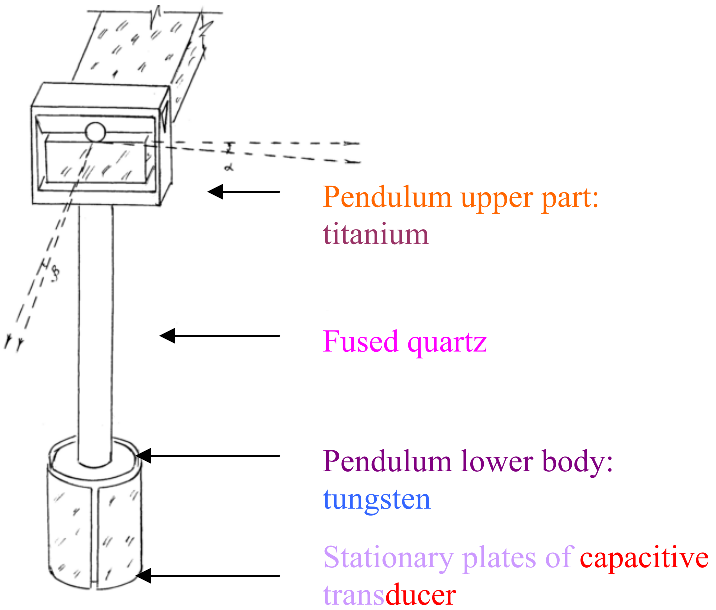

Figure 3: Schematics of the paraconic pendulum

2. Experimental results

In our experiment we used two types of pendulum suspension: the agate sphere and the agate knife, both supported by agate plate. We experimented also with two pendulums of the same construction for which the common regularities were determined. The curvature radiuses of pendulums were 5 and 7 µm. The experiment took place in the building basement on a concrete pedestal.

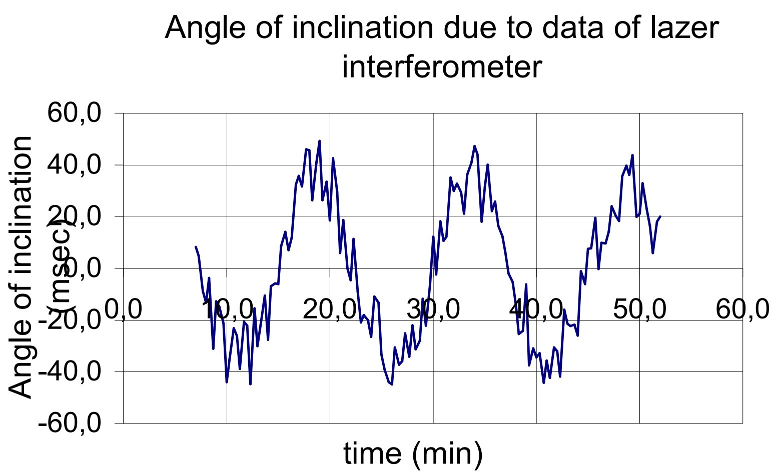

Figure 4: Calibration of the tilting table by means of Laser interferometer.

The tilting table was placed on the crapaudine, and then we measured by laser interferometer the amplitude and period of table tilts which proved to be (0.035±0.007)″ and (15±0.5) min correspondingly (Fig.4).

Spherical suspension

The tilts of pendulums were preset in one plane, and their recording was done in two perpendicular planes. We got as result that the preset tilts cause *parasitic tilts in the perpendicular plane* independently of the azimuth of the device. The amplitudes of parasitic tilts are *comparable* with the preset amplitudes. Even if sometimes there weren't any parasitic oscillation of pendulum in perpendicular plane, the oscillations of *"white noise"* type were always induced with amplitude (0.005 – 0.008)″. Mostly in the perpendicular plane there were the 1st and 2nd harmonics of preset tilts (Fig.5).

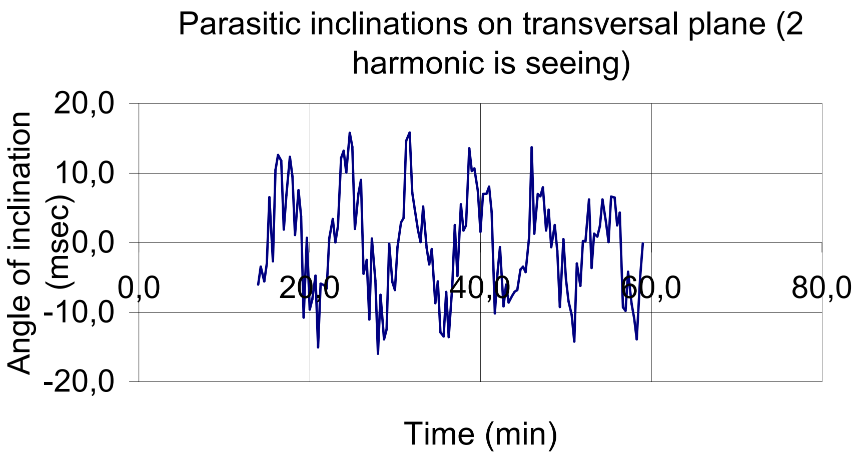

Figure 5: Parasitic inclinations in a direction orthogonal to tilt of platform.

The effect of transfer of pendulum oscillation from plane to plane depends strongly of the quality of treatment of the surfaces of pendulum suspension, and also of the material properties of surfaces. One may suppose that a spherical surface rolls on the plane *bearing on some surface and sphere imperfections* (Fig.6).

Let consider some variants of the positions of contact points. If their position is on the *straight line* in plane of given pendulum oscillations, the latter haven't to transfer from one plane to other. Such case was observed quite seldom. The recording corresponding to this position (see Fig.6a) is given on the Fig.7.

The recording in Fig.5 shows the case corresponding to the Fig.6c where one can see a *duplication of frequency*. All cases were experimentally observed with different azimuthal orientations of device. Because generally the preset tilts of the pendulum in one plane generate the tilts in transversal plane, a tiltmeter with spherical suspension is not of interest until the technology of fabrication of spherical surfaces will be improved.

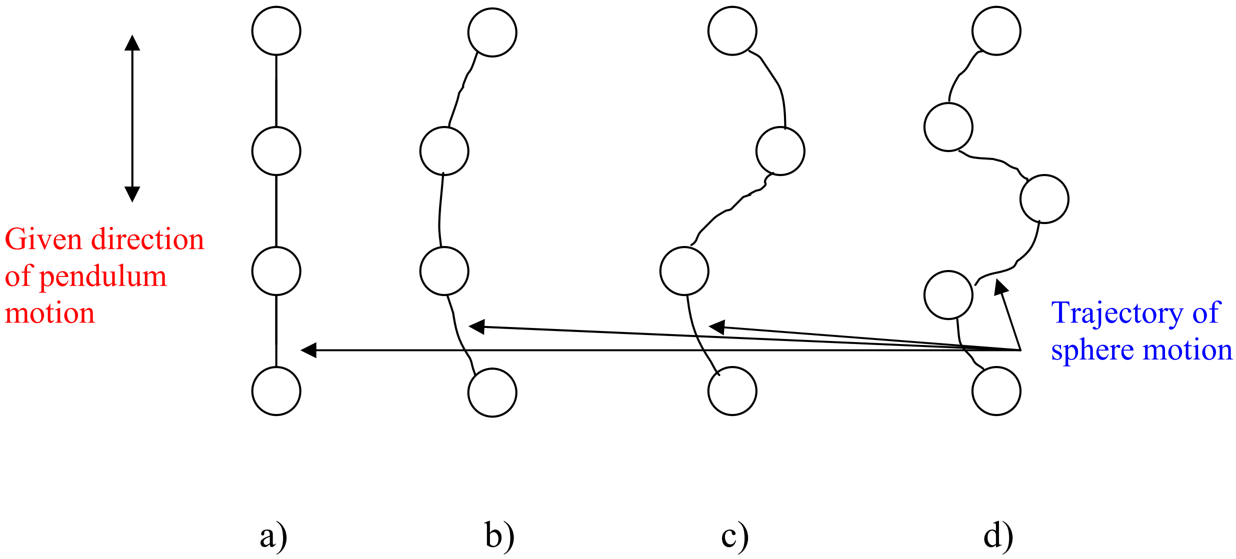

Figure 6: possible trajectories of the sphere on the agate plate.

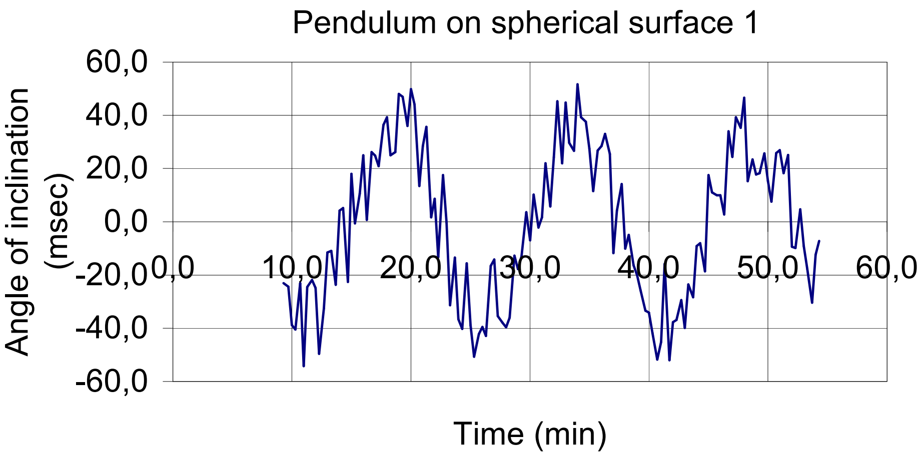

Figure 7: Recording of pendulum with spherical suspension in the direction of tilt.

Knife suspension

The radius of knife curvature was 10 µm, and the length of contact line with the plane was 40 mm; this secures the integrity of the interacting surfaces. By classic calculation (Panteleev, 1959) the decrease of amplitude doesn't exceed 1% for a curvature radius of 10 µm and a pendulum length of 25 cm.

An example of tilt change of pendulum on agate knife is shown in Fig.8.

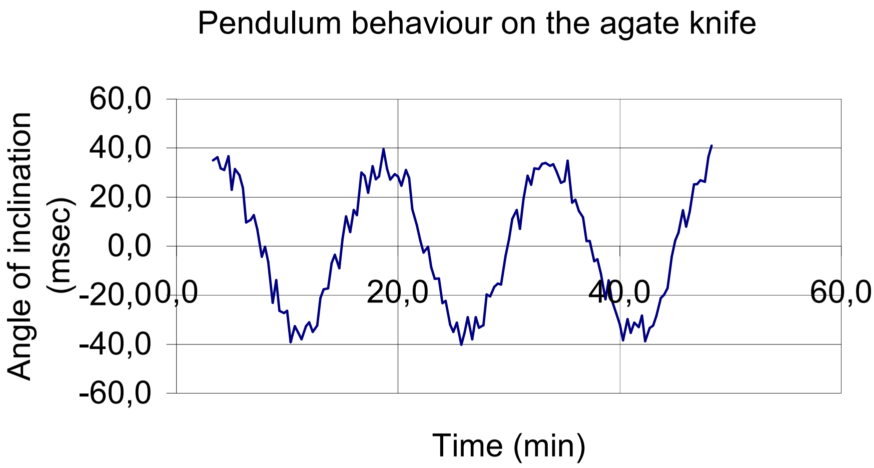

Figure 8: Recording of pendulum with agate knife in the direction of tilt.

One can see that the pendulum repeats a smooth sinusoidal signal given to the base by crapaudine with the error ± 0.003″. By the way the resolution limit of the registration system in our experiment permits to register values <u>*one order of magnitude less*</u>. The received error is related most likely with the quality of treatment of the agate knife and the agate plate on which the knife is rolling. So such pendulum device is a good tiltmeter. Its multiplying factor can be determined experimentally; it depends of tilts interval, multiplying factor of the capacity transformer of displacement, and the radius of knife curvature.

The temperature characteristics of the device, its nonlinearities, interval, resolution limit, and long term stability depend mainly of the characteristics of registration system, of the bonding technique of device on the investigated objects, and so on, and also of the quality and wear and tear of the knife blade and the plate. The construction of this device – in particular the area of contact of knife blade and the plate – is calculated specially for the optimization of the working life of device. The testing was made for big angles of oscillation during hundred hours with a constant control of the change of curvature radius of the knife blade.

Our angles of oscillation are four order less, that's why the long term stability of such tiltmeter related with wear and tear of the knife and plate must be very high.

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