Measurement Techniques, Vol. 38, No. 1, 1995

FUNDAMENTAL PROBLEMS OF METROLOGY

PARACONICAL PENDULUM AS A DETECTOR OF GRAVITATIONAL EFFECTS DURING SOLAR ECLIPSES

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A high-precision, stable, dynamic pendulum-type device created by the present authors and intended for searching for Allais-type gravitational effects is described, and results of an experiment using this device are presented.

The idea of using a paraconical pendulum as a sensing element in gravitational experiments was first proposed by the French scientist M. Allais, 1959 laureate of the American Foundation for Gravitational Research, in the course of experiments intended to study the dynamics of pendulums similar to the Foucault pendulum. Allais created a special construction and carried out observations during the solar eclipses of 1954 and 1959 in Paris [1] during which he noted anomalous behavior in the pendulum's angle of rotation which coincided with the periods of the eclipses.

One of the present authors (L. A. S.) carried out experiments with domestically produced pendulums in 1960-1961 and 1989-1990 [2, 3], and has worked with the second author since 1990. Results of the most recent expedition to Mexico, confirmed by observations of Belgian scientists using high-precision tidal gravimeters, showed that the renewed interest of the scientific community in gravity shielding is no accident. Moreover, the hypotheses that have appeared as a result confirm that we are far from a solution of the problem. The decision was made to, first, create a high-precision, stable, dynamic, portable device, second, develop a technique of eclipse experiments, and, third, verify the existence of the hypothesized Allais effect, that is, disturbances in the motion of a paraconical pendulum during a solar eclipse.

A paraconical pendulum constitutes a heavy though small physical body connected by a short rod to a clip for suspension. Contact of the clip with the pendulum carriage is realized by means of a small sphere or a conical needle which may freely roll in any direction in the carriage's horizontal plane. Thus, it is possible to observe the rotations of a system with three degrees of freedom.

Allais used an asymmetric paraconical pendulum made from bronze and consisting of an upright disk weighing 7.5 kg connected by means of a stem to the clip by means of an open, rectangular, yoke-type configuration. The stem and clip together weighed 4.5 kg, so that when assembled the pendulum weighed 12 kg. The length of the pendulum was found to be around 83 cm. A steel ball-bearing 6.5 mm in diameter that rested freely on the horizontal carriage was used as the suspension member.

In our experiments we applied far shorter pendulums, mainly to ensure that they could all fit inside a vacuum chamber. The pendulums were made from nonmagnetic materials and alloys (niobium, tungsten, titanium, bronze, brass, and quartz), and were from 21 to 31 cm in length, depending on the dimensions of the vacuum chambers. Depending on the configuration and material of the pendulum, the pendulums weighed from 376 to 1320 kg.

The pendulums were produced in the shape of a classical lens-type or cylindrical pendulum. In the first two experiments the clip was similar in shape to that used in the Allais pendulum, though meticulous laboratory testing demonstrated that to

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Translated from Izmeritel'naya Tekhnika, No. 1, pp. 7-10, January, 1995.

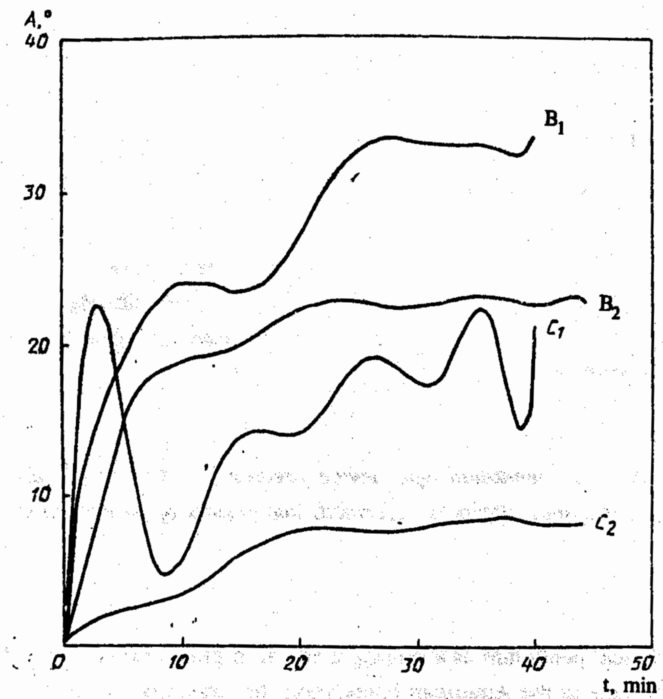

Fig. 1. Dependences of the azimuths on time.

ensure identical launches of all the pendulums, it would be necessary to return to the optimal shape of a closed clip (square or rectangle).

Corundum, agate, and steel conical needles were chosen as the suspension device, more precisely, as the means of freely supporting the pendulum on the surface of the carriage. Small steel spheres measuring from 3 mm for the lightest pendulum to 6.8 mm for the heaviest pendulum were also used.

The motion of the pendulum, understood as a physical body possessing three degrees of freedom, proved to be quite complex. However, the motion of its plane of swinging about the vertical axis passing through the point of instantaneous contact of the suspension device and the carriage reduces, to a first approximation, to the motion of the plane of swinging of a conical pendulum. From the theoretical point of view, the motion of the latter, in turn, may be considered (in the case of small oscillations) as the motion of a spherical pendulum with two degrees of freedom and represented in projections onto the horizontal plane by an ellipse whose major semi-axis coincides with the plane of swinging and which moves by means of time-dependent rotation.

By attaching a bolt to the lower end of the pendulum, Allais was able to observe with the naked eye the path of the pendulum's motion, which appeared to be a flattened ellipse. By means of a camera sight placed in a divided circle he measured the azimuth of the major semi-axis of this ellipse of oscillation.

Inasmuch as all our pendulums had been placed inside evacuated, temperature-controlled chambers and monitored remotely, we decided to use an essentially different method of determining the azimuth of the plane in which the pendulum swings.

The experiment confirmed our hypothesis that it would be better to use a typical closed square- or rectangular-shaped clip rather than an open clip, as in the Allais pendulum. By doing so, we were able to adjust the "lopsided" swinging of the pendulum. That is, a short time after the pendulum had been launched, the azimuth of the plane in which the pendulum's clip swings began to differ markedly from the azimuth of the major semi-axis of the ellipse of oscillation of the lower end of the pendulum, the trajectory of which may be followed by the naked eye along the bolt. Both azimuths vary over time due to the rotation of the pendulum about the vertical axis.

To illustrate these results we present the dependences of these azimuths on time in the case of the pendulum used in the expedition taken to observe the solar eclipse of July 22, 1990 at Belomorsk. Figure 1 depicts curves expressing the azimuth of the clip (C_1) and of the bolt (B_1) for a pendulum equipped with an open clip, and curves expressing the azimuth of the clip (C_2) and of the bolt (B_2) when an open, square-shaped clip was used. Time is measured along the horizontal axis in minutes

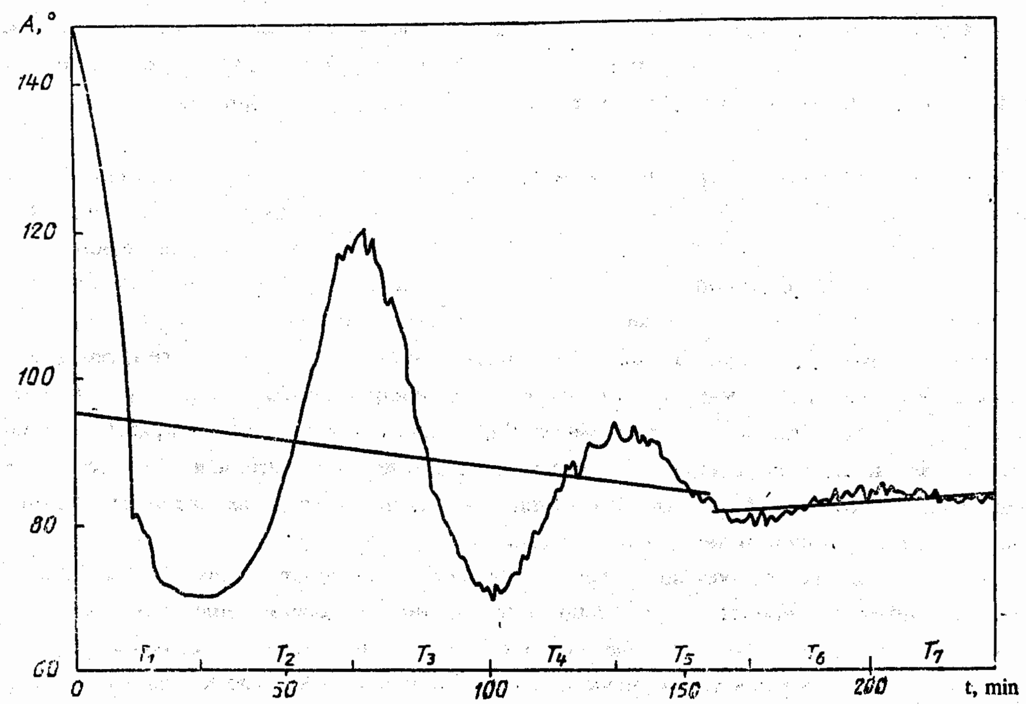

Fig. 2. Dependence of azimuth of major semi-axis of pendulum's oscillation ellipse on time.

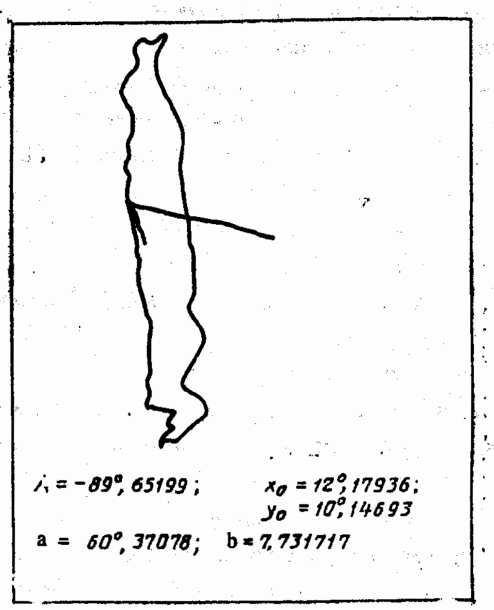

Fig. 3. Approximation of real oscillation ellipse of a pendulum.

and the azimuth A in degrees with a scale division of 1°, starting from an azimuth of 0° (measured from the north–south line in the clockwise direction). In both series of laboratory experiments the pendulum was suspended in the carriage by means of the same small steel sphere measuring 3 mm in diameter. From the curves it is clear that in the case of an open symmetric clip (C_2, B_2), the pendulum's behavior is more stable and the azimuth of the plane of the clip rapidly becomes nearly constant, i.e., the lopsidedness of its motion is slight. Subsequently, through the use of a symmetric pendulum we were able to achieve a situation in which this phenomenon was entirely absent.

It was essential that the point of suspension of the pendulum in the plane of the pendulum carriage lie as close as possible to the vertical axis of symmetry of the pendulum. With the last pendulum construction used during observations of the eclipse on July 11, 1991 in Mexico, we were able to set the point of tangency to within 0.01 mm of the direction of the vertical axis of symmetry.

Using small spheres of different diameters as well as agate and corundum needles as the suspension mechanism, we established that the rate of true rotation of the pendulum about the vertical axis depends on the diameter of the sphere. That is, the greater the diameter, the more rapid the pendulum's rotation. With a sharp enough needle, essentially a sphere with vanishingly small diameter, and a large enough pendulum, true rotation almost does not occur, and only a variation in the azimuth of the major semi-axis of the ellipse of oscillation of the lower end of the pendulum is observed. In [2] it was proved that this occurs as a result of pivoting friction. Quantitative estimates of this form of friction were given in the article.

In [6] the influence of the anisotropy of the carriage on the pendulum's motion was investigated. It was established that the mean position of the major semi-axis of the oscillation ellipse tends to lie in a direction parallel to that of the plane of maximal elasticity of the carriage; the azimuth of this plane is natural to each instrument. As a result the motion of a paraconical pendulum does not resemble the motion of a Foucault pendulum, inasmuch as anisotropy acts first in the same direction as the Foucault effect, and then in the opposite direction.

Repeated laboratory experiments have shown that as a paraconical pendulum moves, the oscillation ellipse rotates alternately clockwise and counterclockwise, changing direction when the ellipse degenerates into a line. Denoting by T_i the time the oscillation ellipse rotates in one direction from one line to another, we may trace the periodicity of the change in the direction of rotation from the time the pendulum is launched until it completely halts. The azimuths of the degeneracy lines of the ellipse define the sector in which it rotates. Because of the existence of rolling and pivoting friction between the suspension and the carriage, the rotation sector gradually shrinks, degenerating (in the limit) to a line that coincides with the direction of the maximal elasticity of the carriage.

Figure 2 presents a curve representing the time dependence of the azimuth of the major semi-axis of the pendulum's oscillation ellipse. One of the longest series of laboratory experiments (4 hours 7 minutes in length) was selected prior to the onset of the eclipse. The time t in minutes is laid out along the horizontal axis at intervals of 5 min. Values of the azimuth expressed in terms of degrees are laid out along the vertical axis at intervals of 2°. It is clear that the direction of rotation of the oscillation ellipse changes seven times, T_i assuming the following values: $T_1 = 38$, $T_2 = 40$, $T_3 = 33$, $T_4 = 31$, $T_5 = 34$, $T_6 = 32$, and $T_7 = 33$ (min). The mean position of the plane in which the pendulum swings is represented by the sloping line. Note that this plane tends to become parallel to the direction of the plane of maximal elasticity of the carriage. The azimuth of the latter plane for the given construction was equal to 84°.

Recording Pendulum Oscillations. Allais relied on observation of the trajectory of the pendulum with the unaided eye. The pendulum halted every 14 minutes in his experiments, and, using a camera sight aimed along a divided circle he determined the azimuth of the plane of swinging to within 0.1°.

We photographically recorded a pendulum's oscillations in the course of observations undertaken during the 1961 and 1990 eclipses. In 1961, a track in the film was obtained in the form of an analog of a sinusoidal damping sweep for a moving pendulum. The track was constructed using a contract breaker that caused light to shine for 4 sec every 10 min. In 1990, due to a lack of time, we were not able to construct a contract breaker, and therefore photographic recording was done continuously; instead, we compared the strength and type of density of the photographic film. However, we nevertheless were ableto createan optico-electronic record ofthe oscillation ofa pendulumusing electronic recording on computer for the first time.

An optico-electronic element is a photo-sensitive plate in the form of a square measuring 1 × 1 cm in area. There are + four current-collecting electrodes deposited along each side of the square. The patch of light incident on the photosensitive layer produces electric currents. The strength of these currents depends on the distance between the light patch and the current-collecting electrodes. The closer the light patch is to the electrode, the more powerful is the current that may be taken from this electrode. By assuming that the Cartesian coordinate (x, y) plane coincides with the surface of the sensor and placing the coordinate origin in the center of the square, we created a signal pick-up system with each coordinate proportional to the difference signal from opposite electrodes. At the center of the sensor the currents are equal and x, y = 0, while the deviations from the center are determined by means of the following expressions:

$$x = \frac{I_1 - I_3}{I_1 + I_3}, \quad y = \frac{I_2 - I_4}{I_2 + I_4},$$

where I_1, I_2, I_3, and I_4 are the currents through the corresponding electrodes.

Because of special features in the construction of the device used to make observations at Belomorsk on July 22, 1990, the light patch rapidly escaped from the surface of the sensor. Therefore, photoelectronic computer recording was undertaken only for the first three seconds so as to control the launch of the pendulum.

Using the experience we had acquired, we were able to create a completely computerized and automatic system for recording pendulum oscillations during the eclipse of July 11, 1991 in Mexico. Principles governing the design of an optical bridge and information pick-up from the photoelectronic sensor were defined and the filtration circuits and software were upgraded.

The system was designed to pick up and record information every 30 seconds for 8 hours. For all four currents, the recording step was set equal to 0.125 sec. Since the pendulum's natural oscillation period was 1 sec, 64 measurements for the pendulum's eight oscillation ellipses were accumulated in 8 sec. Each measurement exhibited a random error whose magnitude was determined by the noise of the electric currents taken off the electrodes, the precision with which the opposite electrodes were adjusted, and the time it took to build-up charges or the measurement time. The greater the current noise and the less the charging time (measurement time), the greater the error. It was possible, for example, to set the build-up time equal to 0.250 sec, rather than 0.125 sec. The error associated with determination of the position of the light patch was halved, though the number of measurements over this period of time was also halved, i.e., the approximation of the actual oscillation ellipse worsened.

From each measurement of the four currents, the computer calculated the coordinate pair x, y and plotted them on the screen, simultaneously recording the values of the coordinates in memory for subsequent essential calculations. Figure 3 represents an approximation of an actual pendulum oscillation ellipse on the basis of 64 pairs of coordinates obtained in the course of a typical eight-second observation period. The numbers at the bottom of the figure correspond to the azimuth of the major semi-axis A, the coordinates of the center of the ellipse x_0, y_0 relative to the center of the sensor, as well as the major and minor semi-axes (expressed in terms of conventional units) calculated expressly for this figure. Thus, we were able to observe on the computer screen the motion of the pendulum's oscillation ellipse as described earlier in this article, specifically, the line at the launch time, the appearance of the flattened ellipse and the rotation of the ellipse in the plane of the computer screen, the swelling of the ellipse to a maximum followed by its flattening and the degeneracy of the ellipse into a line, with the process subsequently repeating, the ellipse now rotating in the opposite direction.

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