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ASTRONOMICAL CLOCK AChF-1 WITH ISOCHRONOUS PENDULUM

F. M. Fedchenko

The astronomical pendulum clock AChF-1, developed by the author, differs from existing astronomical clocks(manufactured by the factory "Etalon" and the firm "Synchronome Ltd") in its simplicity of construction and high accuracy. The root-mean-square variation of its daily rate is less than 0.001 sec per day, i.e., it is much more accurate than existing first-class astronomical clocks.

AChF-1 works without a secondary clock; therefore, there is no need to synchronize the pendulums.

The accuracy of its rate is achieved by the use of a special three-spring isochronous pendulum suspension and a mechanism which delivers short mechanical or other impulses to the pendulum in its equilibrium position. Such a mechanism does not disturb the isochronism of the pendulum oscillation, which is attained by means of the suspension.

The principle of action of the isochronous suspension, and also that of the impulse mechanism with mechanical impulses, is described. Curves of the clock rate for November-December, 1955, and of variations due to gravity obtained by means of the astronomical clock, are given.

The AChF-1 clock can be used as a timekeeper and also as an instrument for observing variations of gravitational acceleration.

At the present time the astronomical pendulum clock whose use is most widespread is that of Shortt, manufactured by the English firm "Synchronome Ltd." A clock of similar construction in the Soviet Union is manufactured at the Leningrad factory "Etalon." The root-mean-square variation of the daily rate of the Shortt clock reaches ± 0.002 to 0.003 sec per day. Shortt's clock is complicated in construction. It consists of a primary and a secondary clock. The secondary clock exists solely to maintain the pendulum oscillation of the primary clock. The primary synchronizes the pendulum oscillations of the secondary clock. A small disturbance of pendulum synchronism leads to a deterioration of the clock rate, and sometimes to stopping the clock.

In the time laboratory of the Kharkov State Institute of Measures and Measuring Instruments (KhGIMIP), during 1954 and 1955, the author developed and built an astronomical pendulum clock of new design, the AChF-1, which differs from existing astronomical clocks in its simplicity and high accuracy. The root-mean-square variation of its daily rate is less than 0.001 sec by comparison with the KhGIMIP quartz clock, that is, it is much more accurate than existing first-class astronomical pendulum clocks. Accuracy is due to the following:

1. A high degree of pendulum isochronism through the use of an isochronous pendulum suspension.

2. Freer oscillation of the clock pendulum, attained through minimal coupling to the mechanism, and through the use of infrequent short impulses imparted to the pendulum at its equilibrium position.

3. Impulses of high constancy both in magnitude and in the phase at which they are imparted to the pendulum.

The AChF-1 functions without an auxiliary clock; hence there is no need for synchronization of the pendulums. A general view of the clock is shown in Fig. 1.

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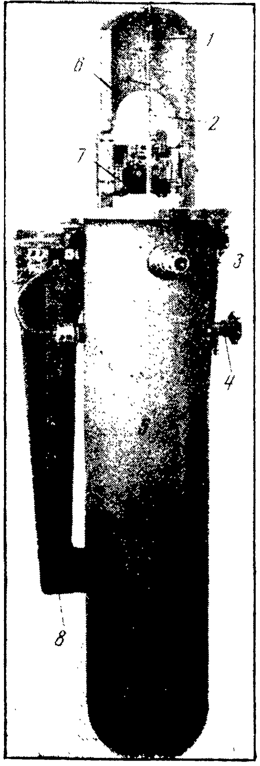

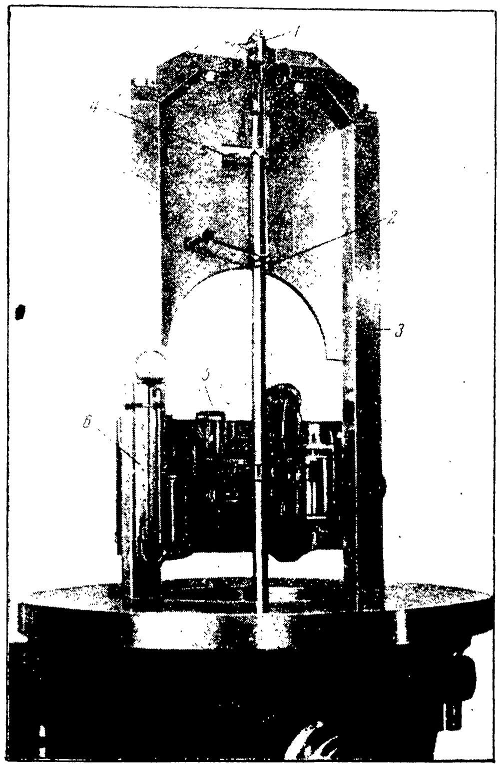

Fig. 1. Fedchenko AChF-1 astronomical clock; 1) isochronous pendulum suspension; 2) pendulum; 3) microscope for amplitude observations; 4) vacuum valve; 5) pressure chamber; 6) suspension bracket; 7) clock mechanism; 8) clock bracket.

Fig. 2. Upper part of the AChF-1 clock; 1) isochronous pendulum suspension; 2) pendulum contact; 3) suspension bracket; 4) lowering mechanism; 5) clock mechanism; 6) manometers (mercury and oil).

The clock is mounted in a steel pressure chamber 5, which is rigidly attached in the vertical position to the wall or to a clock column by means of a cast-iron bracket 8. On the cover of the pressure chamber is set the suspension bracket 6, from which the pendulum 2 is suspended by means of the isochronous spring suspension 1, and to which the clock mechanism 7 is also attached. There are located on the pressure chamber a microscope 3 for observations of the amplitude of the pendulum oscillations, a vacuum valve 4 for exhausting air from the pressure chamber, and a panel for the entry of conductors to the mechanism. Within the pressure chamber are located the spark suppressors of the mechanism contacts and a light bulb which illuminates the pendulum scale during measurements of the amplitude of oscillation.

The clock is covered by a glass dome and the pressure in the chamber is reduced to 8 to 10 mm Hg. The clock is operated from a 10 to 12 v storage battery.

An enlarged view of the upper part of the clock is shown in Fig. 2. On the left-hand column of the suspension bracket are placed the mercury and oil manometers 6 for readings of the pressure within the pressure chamber. On the bracket plate is placed the contacting stop 2 of the clock contact and a checking mechanism 4, by means of which the pendulum is lowered onto the suspension. The columns and plate of the suspension bracket are made of steel and are chrome-plated.

Isochronous Pendulum Suspension

The period of oscillation of a clock pendulum varies with the amplitude of its oscillation, i.e., the oscillations of the pendulum are not isochronous. Since the amplitude of pendulum oscillations is not constant, the clock rate will change correspondingly.

To achieve fully isochronous oscillations of the pendulum it is necessary for the restoring moment to be proportional to the angle of deflection of the pendulum. In reality, however, the pendulum is acted on by a total moment consisting of the normal restoring moment due to gravity, which is proportional to the sine of the angle of the pendulum deflection ($M = k \sin \Phi$), and the elastic moment of the spring suspension, which is proportional to the angle of deflection of the pendulum ($M = k_1 \Phi$). Expanding $\sin \Phi$ in a series limited to the first

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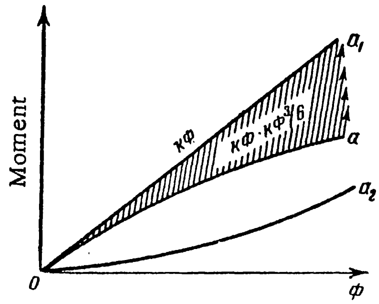

Fig. 3. Restoration moment as a function of pendulum amplitude.

two terms, we have $M = k\Phi - k\Phi^3/6$. Consequently the natural restoring moment is less than that required to produce complete isochronism by the quantity $k\Phi^3/6$, which is proportional to the cube of the amplitude. Figure 3 illustrates qualitatively the difference between the restoring moment $k\Phi - k\Phi^3/6$, represented by the curve Oa, and that necessary for complete isochronism $K\Phi$, represented by the straight line Oa_1. The area between these curves Oaa_1 gives a qualitative representation of the insufficiency of the natural restoring moment for isochronism of the pendulum oscillations.

The question of isochronism of pendulum vibrations has attracted theoreticians as well as horologists from the time when pendulums were first used in clocks, and many different mechanisms have been proposed at various times for its solution.

Huygens (1673) proposed cycloidal guides for the suspension springs during swinging of the pendulum.

Barth (1787) proposed rolling an additional weight over a cylindrical surface whose axis is situated below the axis of rotation of the pendulum.

An additional spring was proposed which the pendulum would stretch while swinging.

Many other devices were also proposed but none of them came into widespread use, since either they themselves added a larger error than the error which was to be corrected or else they were complicated and impractical.

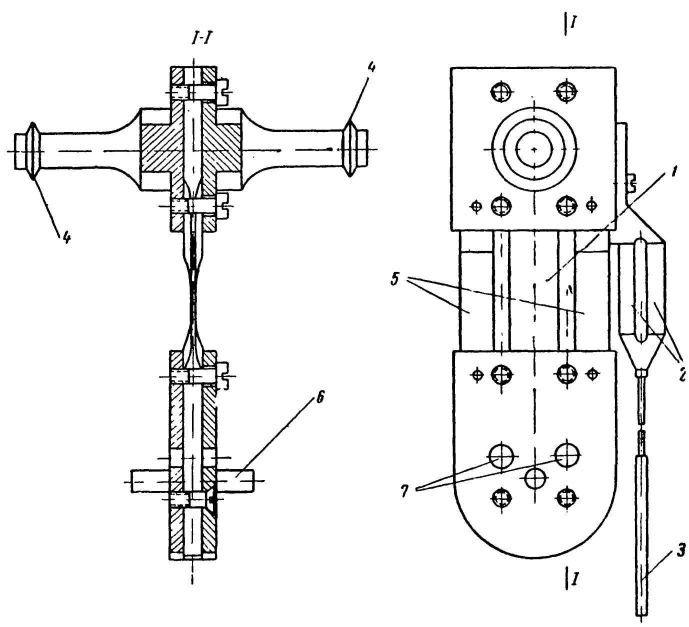

Fig. 4. Isochronous pendulum suspension. 1) Long spring; 2) contact springs; 3) contact rod; 4) bosses; 5) short springs; 6) lower suspension pin; 7) openings for screws to tighten sides of the suspension hook of the pendulum.

The assertion in the literature that a sufficient degree of isochronism of pendulum oscillations can be obtained by the selection of suitable dimensions and shapes of the suspension springs is based on a misunderstanding. In investigations carried out in support of this idea, only composite suspensions were used which permitted loose contact between the sides of the suspension and the thin springs.

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This also explains the result obtained by Khain [1, 2] in experiments where a thin suspension gave overcompensation and a thick one undercompensation.

By adjusting the compression of the upper parts of the sides of a composite suspension by means of screws, different degrees of isochronism can be obtained. When there is tight upper contact with the springs, no isochronism whatever is observed. Also, one-piece suspensions provide no isochronism whatever. Isochronism obtained by using a composite suspension is an index of the poor quality of the suspension rather than of its advantage.

Numerous experiments conducted with various suspensions have confirmed that isochronism of oscillations of a free pendulum cannot be attained by altering either the dimensions or the shape of the springs of the suspension.

In order to obtain isochronous oscillations of a free pendulum, the author in 1952 developed and built an isochronous suspension, whose design is shown in Fig. 4. Unlike ordinary nonisochronous two-spring suspensions the isochronous suspension consists of three springs 1,5, situated in the plane of, and symmetrically arranged with respect to the longitudinal axis of the suspension. The middle spring is longer than the outside ones and displaced upwards. The three springs represent separate one-piece suspensions, joined in their thick portions by plates, screws, and pins. The middle spring can be moved along the longitudinal axis of the suspension, providing regulation of the degree of isochromism. Moving the middle spring upwards increases the isochronous properties of the suspension, moving it downwards decreases them. If the upper parts of all three springs are located at the same height, the usual nonisochronous suspension is obtained. The suspension pins are tied by plates. The upper pin possesses circular bosses 4, on which the suspension rests in the working position.

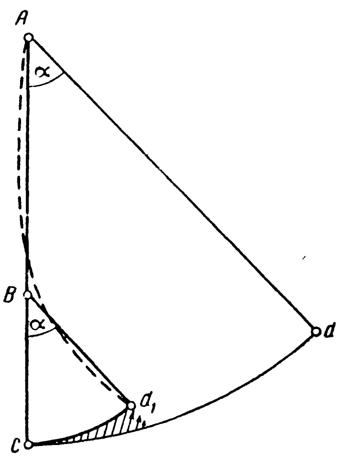

Fig. 5. Diagram of the principle of action of the isochronous suspension.

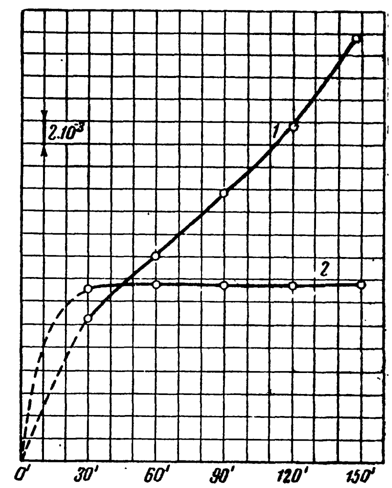

Fig. 6. Dependence of the pendulum period on amplitude: 1) for an ordinary suspension; 2) for the isochronous suspension.

For a qualitative idea of the principle of operation of the isochronous suspension let us examine the scheme shown in Fig. 5. AC is the long spring, BC is a short spring of the suspension. The springs are firmly pressed at their ends and no relative displacement is possible. Let point A be the projection of the axis of rotation of the pendulum, suspended only by the long spring in the absence of the outside springs. Point B is the projection of the axis of rotation of the pendulum suspended only by the short springs in the absence of the long one. If the pendulum is suspended by the long spring, then the lower end of the spring (point C), when the pendulum swings to the right through an angle α, would be transferred to the point d along the arc Cd. If the pendulum were suspended only by the short springs, then their lower ends (point C), with the same angle α of pendulum swing, would be moved to the point d_1 on the arc Cd_1. In actuality, however, the pendulum is suspended by the three springs, which are rigidly fastened to each other; thus the end of the long spring, when the pendulum swings, is forced to follow the path of the short springs Cd_1, and the long spring is forced to bend as shown by the dashed line Ad_1. Hence the middle spring, in addition to the common deformation caused by the pendulum swing in all three springs, undergoes a further deformation caused by the different lengths of the springs and the noncoincidence of the points at which they are fastened.

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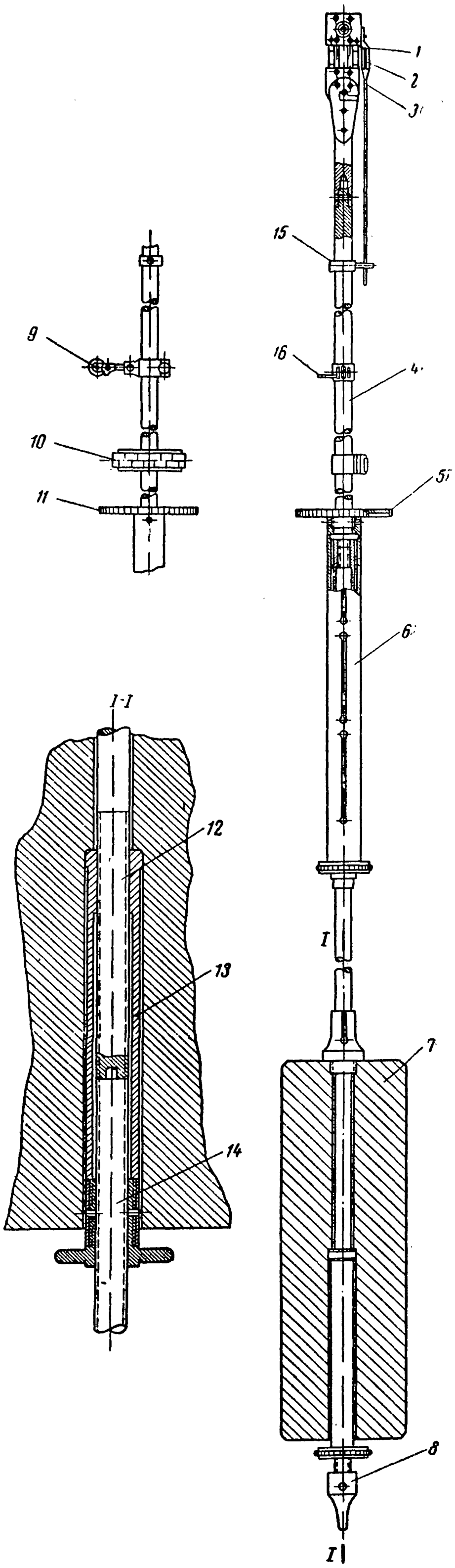

Fig. 7. Pendulum of the AChF-1 clock. 1) isochronous suspension; 2) contact springs; 3) contact rod; 4) pendulum rod; 5,11) platform for regulating weights; 6) temperature compensating tubes; 7) pendulum bob; 8,14) regulating nut; 9) impulse roller; 10) scale for observations of amplitude; 12) lower end of rod; 13) tube supporting pendulum bob; 15) pin, withdrawn; 16) release projection.

Area Cdd_1 in the figure gives a qualitative representation of the additional deformation of the longer middle spring. This deformation increases with an increase of amplitude more rapidly than in proportion to the displacement angle of the pendulum. This means that the common restoring moment of the isochronous suspension will increase more rapidly than in proportion to the displacement angle of the pendulum, i.e., along the curve Oa_2, which in a certain interval of amplitudes is symmetric with the curve $k\Phi - k\Phi^3/6$ (Fig. 3).

The combined effect of the natural restoring moment and the restoring moment of the isochronous suspension in the given interval of amplitudes is expressed by the straight line $K\Phi$, which is the condition for isochronism of the pendulum oscillations. Thus the isochronism of this suspension is caused by the presence of the longer third spring whose additional deformation supplies an additional elastic moment in a certain, sufficiently wide, range of amplitudes to compensate the insufficiency of the natural restoring moment.

The period of oscillation of the pendulum with the isochronous suspension is independent of the amplitude in the required amplitude range, as is seen from Fig. 6. Curve 1 shows the dependence of the pendulum period on amplitude with an ordinary suspension when freely damped; curve 2 shows that with the isochronous suspension.

The isochronous properties of the suspension depend entirely on the elastic properties of the springs, so that the springs must be manufactured of a suitable grade of steel and receive the necessary heat-treatment.

Isochronous characteristics obtained before installing the suspension in the clock, and after one year's and two year's running, coincided completely, which testifies to the stability of its operation. Temperature changes also have no effect on the isochronous properties of the suspension.

The Pendulum

The clock pendulum is of the usual two-second type with a ten-millimeter invar rod 4 and cylindrical copper bob 7, with a total weight of 10 kg. The construction of the pendulum is shown in Fig. 7.

The pendulum is equipped with an exposed adjustable temperature compensator made of thin tubes, the inner one being of brass and the outer one of invar. The tubes are coupled by means of a flat thread and provided with a retainer nut. The pendulum rod is cut apart and the outer invar tube is a continuation of its upper part. The lower part is

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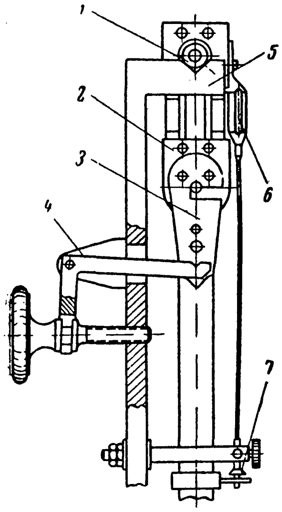

Fig. 8. Mechanism of the pendulum suspension: 1) annular bosses of the upper suspension pin; 2) isochronous suspension; 3) hook for suspending the pendulum rod; 4) lowering mechanism; 5) suspension cock with longitudinal groove, on which the annular bosses of the suspension rest at points a and b; 6) contact springs; 7) contact stop.

inserted into the end of the brass tube. The threads in the temperature compensator tubes and in tube 13, which supports the pendulum bob, are of the same pitch. This is convenient for regulation. If there should be any need to decrease the action of the temperature compensator, then one unscrews the tubes several turns relative to each other and, in order to maintain the former pendulum length, tube 13, must be given the same number of turns on the rod.

The tube carrying the pendulum bob is also of invar and is threaded at both ends. The upper thread 12 is used to screw it on the pendulum rod and the regulating nut 8 screws into the lower end. This brings about coincidence in the direction of the stresses that arise in the tube under the action of the weight of the bob and of the regulating nut.

The outer tube of the temperature compensator 6 has longitudinal slits on opposite sides to permit circulation of air around the inner tube. By this means thermal inertia is kept to a minimum in the pendulum.

The upper part of the outer tube of the temperature compensating tube ends in a platform 5, 11, on which are placed the regulating weights. The rod is coupled to the tube and also to the suspension hook by screw threads and pins.

Above the platforms are located the scale 10 for observations on the amplitude of pendulum oscillations, the impulse roller 9, and the contact-breaking pin 15.

The impulse roller is of steel with diameter of 5 mm. It turns on thin arbors in 4 jewels. In order to eliminate the effect of possible eccentricity on the clock rate, the roller is unbalanced. On the roller rod is placed the release projection 16, by means of which the pendulum periodically knocks out the rest from under the impulse arm of the clock mechanism, thus preparing the impulse. The release projection is so fastened that it is movable on the roller stem, by which means regulation of the size of the impulse is achieved. By moving the projection toward the roller the impulse is decreased, and by moving it away from the roller, it is increased.

The upper part of the pendulum rod ends in the hook of the suspension between the sides of which the isochronous pendulum suspension 1 is inserted.

A light contact is fastened by the thin springs 2 to the upper part of the suspension. When the pendulum moves to the right, the rod of contact 3 rests on the deflecting pin 15 and is inclined at the angle of inclination of the pendulum; in displacement of the pendulum to the left it rests on the contact-stop situated on the plate of the clock suspension bracket (Figs. 2 and 8). The contact is closed for half the period and open for half the period. The axes of rotation of the pendulum and of the contact coincide, thus eliminating the possibility of harmful friction arising between the contact rod and the pin which deflects it. This kind of contact takes no energy from the pendulum (apart from internal friction) since the energy expended by the pendulum in deflecting the contact returns to it in the reverse movement, exactly as occurs in the suspension itself. The place of contact is closely adjusted to the equilibrium position of the pendulum; hence the contact cannot affect the period of vibration of the pendulum at all.

The mechanism of the clock works from this contact through a high-resistance relay. It is also used for comparing clocks. Contact spread does not exceed 0.1 msec. The current broken by the contact is small (of the order of 1 to 2 ma). The pendulum contact is provided with its corresponding spark suppressor, as are all other contacts of the impulse mechanism of the clock. To avoid the possibility of chance damage to the

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isochronous suspension during installation, the suspension bracket has a checking mechanism 4, with the help of which the pendulum can be smoothly lowered onto the suspension.

The sides of the hook 3 are tightened by screws through openings in the lower part of the suspension, thus providing a firm connection of the pendulum to the suspension. By means of the annular bosses 1, the suspension is seated at four points on the wall of the longitudinal groove in the bracket 5 (seen at a and b). This method of suspending eliminates the possibility of longitudinal oscillations of the pendulum arising in the plane perpendicular to its basic oscillations, and also serves to damp possible vertical jolts to the suspension.

The mechanism for suspending the pendulum is shown in Fig. 8.

The Clock Mechanism

A positive impulse imparted to the pendulum after its equilibrium position lengthen its vibration period, while a positive impulse imparted before the equilibrium position shortens its. The action of a negative impulse is opposite. The effect depends also on the phase of delivery of the impulse. The further the pulse is from the equilibrium position of the pendulum, the greater its effect and, vice versa, the nearer the less. Only impulses given to the pendulum at its equilibrium position have no effect on the period of oscillation.

The pendulum oscillations of the AChF-1 clock are isochronous, and therefore the mechanism maintaining its oscillations is subject to special requirements. The impulse mechanism of the clock which maintains the pendulum oscillations must not counteract what is achieved by the use of the isochronous suspension. Existing mechansims do not satisfy this requirement. Only a mechanism giving the pendulum short impulses exactly at the equilibrium position, irrespective of the nature of the impulses, can do so.

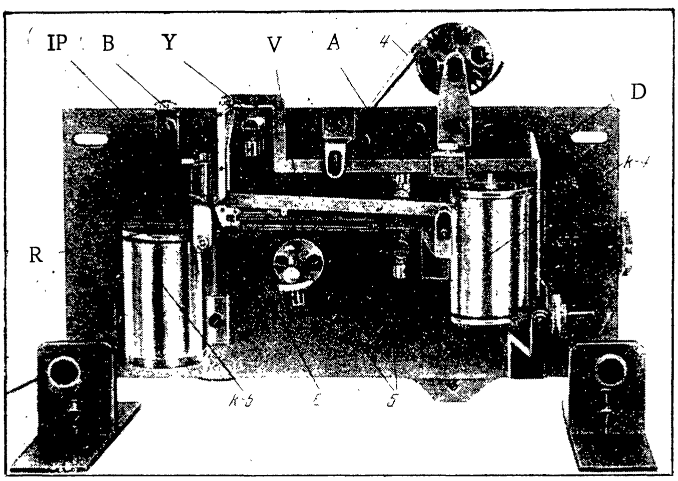

Fig. 9. Impulse mechanism of the clock; IP) impulse pin; B) hook; Y) support; V) impulse lever; A) preparing lever; 4) contact of the impulse transmitting mechanism; D) catch; K-4) electromagnet coil; 5) contacts of the restoring lever; E) movable lobe; K-5) electromagnet winding; R) restoring lever.

Any change in the magnitude of the short impulses, whether positive or negative, given to the pendulum at its equilibrium position, can only affect the amplitude. But changes of amplitude are compensated by the isochronous suspension. It was this which provided the possibility of eliminating the secondary clock, entrusting some additional functions to the pendulum of the AChF-1 clock.

Only a pendulum with period independent of the clockwork can be called free. In this sense, the pendulum of the AChF-1 clock, despite its fulfillment of certain additional functions, is freer than the free pendulum of the Shortt clock, since the oscillations of the latter are maintained by long impulses given after the equilibrium position.

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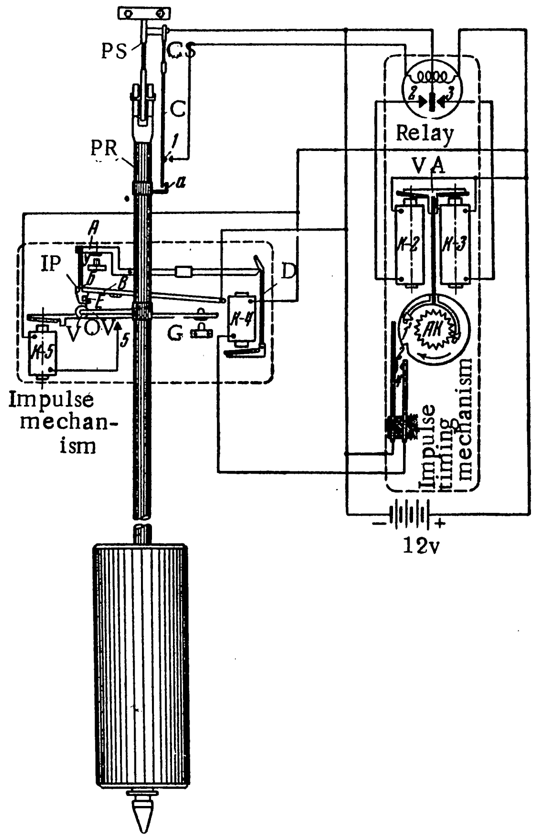

Fig. 10. Schematic diagram of the Fedchenko astronomical clock.

The AChF-1 clock contains a newly developed mechanism which gives to the pendulum in its equilibrium position short infrequent mechanical impulses of a duration which does not exceed 0.01 sec, while in the Shortt clock it reaches 0.4 to 0.5 sec. In the Shortt clock impulses are given every 30 sec and in AChF-1, every 60 sec.

The mechanism of the clock consists of an impulse mechanism (Fig. 9) and the mechanism for impulse timing. A schematic diagram of the clock mechanism is shown in Fig. 10.

In the process of oscillation the pendulum, by means of the deflecting pin a and the rod b, periodically closes and opens the contact of the pendulum 1. The polarized relay thus brought into play alternately passes current to the windings of electromagnets K-2 and K-3, as a result of which the escape yoke VA is attracted and drives the escape wheel AK. The latter has 30 teeth and makes one revolution every 60 sec. The axle of the escape wheel also bears a disk with a notch 2'. At coincidence of this notch with the 1' projection located on the contact spring of the impulse timing mechanism, the contact 4 closes. The current then enters the winding of the electromagnet K-4 with the help of which the catch D is deflected, freeing the lever A. At the left-hand end of the lever A is a light hook B, ending in the movable lobe E. On a projection of the hook (the impulse pin IP) rests the impulse lever V. Lever A, on release of the catch D, under the weight of the impulse lever V, is rotated around its axis so that its left end seats on the stop Y. E comes into engagement with the release projection of the pendulum OV, which is on a rod bearing the impulse roller IR. When the pendulum moves to the left, E is deflected and the pendulum continues to move freely. When the pendulum moves to the right, OV touches E and knocks out the hook B from under the impulse pin, thus freeing the impulse lever V. In falling, the impulse pin of the lever touches the impulse roller IR tangentially, communicating the pulse to the pendulum, after which it rests on the contacting stop and closes contact 5. Lever A at this time occupies its initial position, clamped by D. Contact 5 directs current to the winding of electromagnet K-5, which by means of lever R throws the impulse lever into its original position. The cycle described is repeated with each turn of the escapement wheel.

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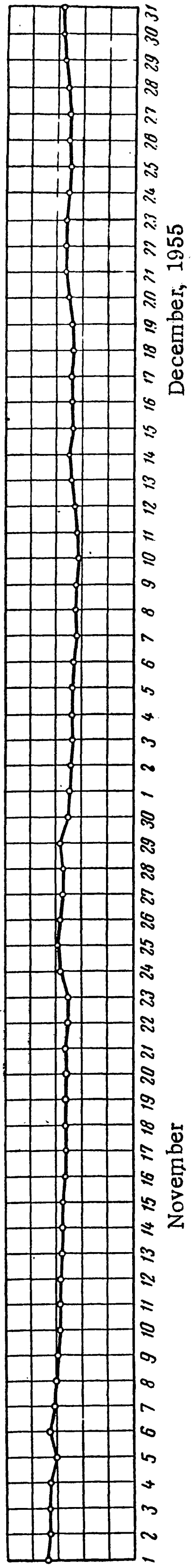

Fig. 11. Daily rate of the AChF-1 clock (Division: 0.10 sec).

The clock mechanism is mounted on an iron plate which is simultaneously a magnetic screen, protecting the pendulum from the electromagnetic field of the electromagnets in the impulse timer, which is mounted on the other side of the plate. In addition all electromagnets are encased in iron.

The levers of the mechanism are of brass. All crucial rubbing parts of the mechanism are mounted on jewels. The contacts of the mechanism are of platinum. The exact timing of the impulses relative to the equilibrium position of the pendulum is regulated by a micrometer which moves the clock mechanism as required.

Study of the Clock

In the absence of a special clock vault, the AChF-1 clock was placed on the wall of the basement room of the working building of the KhGIMIP. The clock room was not thermostatically controlled and thus the annual temperature variation reached 5 to 6°. In addition, during the winter, large daily oscillations were observed on account of nonuniform heating. Only in summer was the temperature of the room maintained more or less satisfactorily, i.e., it changed smoothly by 0.1 to 0.2° per day. A story higher, on the wall where the clock was located a motor and fan were operated periodically.

Under these conditions the clock worked for a period of almost three years while it was being studied. During this time it never stopped spontaneously. The temperature coefficient of the clock is found in the vicinity of − 0.004 sec/°C.

The clock was compared daily by means of a spark chronoscope accurate to 0.1 millisec, with a KhGIMIP quartz clock (KKh-3). The root-mean-square variation of the daily rate for a period of time when the temperature of the room changed smoothly did not exceed 0.001 sec per day. The rate of the AChF-1 is shown in Fig. 11, which gives the daily rates for November and December of 1955. Divisions on the vertical axis represent 0.01 sec. Under appropriate conditions the stability of the rate of this clock would undoubtedly be better. A perfect astronomical pendulum clock must in its rate follow accurately the variations of the acceleration due to gravity. How closely the clock AChF-1 approaches this can be seen from Fig. 12, which gives curves of the dependence of the clock rate on lunisolar variations of gravity.

The curves were obtained by comparing the AChF-1 clock with the quartz clock KKh-3 in a special program where the intervals between comparisons are equal fractions of a lunar day. The error of the comparisons is ± 0.1 millisec.

Three series of comparisons were performed in 1954:

1. November 13, 14 and 15;
2. November 25 and 26;
3. December 10, 11 and 12.

Full moon fell on November 10, new moon on November 25, and full moon again on December 10. In the figure time intervals are plotted along the horizontal axis in fractions of a lunar day. One division is equal to 3 hours 7.5 min, and 3 hour 6 min. in the second series. The clock rate was taken after every two intervals and, on the graph, is plotted for every interval. One division of the vertical axis corresponds to 0.001 sec.

The variation in period of the pendulum is related to the variation of gravity by the formula $\Delta T/T = -\frac{1}{2}(\partial \Delta/\partial)$, whence the time for which a change of gravity of 0.01 milligal can be detected (which in the ratio corresponds to 1×10^{-8} when the accuracy of measurement of the period of the clock pendulum is 1×10^{-4} sec), is

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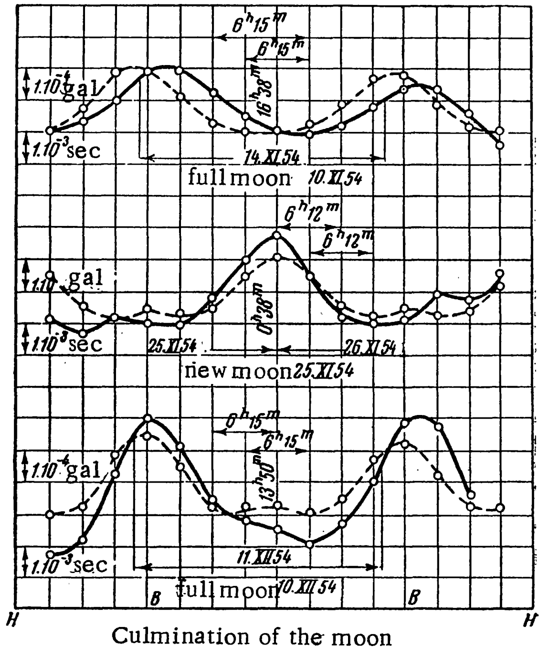

Fig. 12. Curves of observations of gravity variations by means of the AChF-1 pendulum clock; 1(continuous line) observation data; 2)(dashed line) calculated data.

$2 \times 10^{-4} \times 10^{8} = 2 \times 10^{4}$ sec or 5.5 hour. Thus a change of the clock rate during two intervals (6 hours 15 min) with small daily variation determines a variation of gravity up to 0.01 milligal. The results of the comparison of the pendulum clock with the quartz one are plotted in the graph by a continuous line.

The dashed line marks the approximate values of the corrections for gravity at Khar'kov for the lunisolar effect calculated from the tables of P. F. Shokin and according to the Astronomical Annual for 1954. The corrections are calculated to hundredths of a milligal and reckoned from the moment of time of comparison of the clocks. On the vertical axis one division corresponds to 0.1 milligal.

The calculated corrections were given by the director of the Poltava Gravimetric Observatory (Z. N. Aksent'eva).

As seen from the drawing, the curves obtained experimentally and by calculation in all three cases differ little from each other. If a group of pendulum clocks were used in these observations, the coincidence of the curves would be much better on account of the averaging of the rates.

Further investigation of the clock AChF-1 and its improvement were transferred from the KhGIMIP to the All-Union Scientific Research Institute of Physicotechnical and Ratiotechnical Measurements (VNIIFTRI). At present an astronomical pendulum clock AChF-2 already exists that differs from AChF-1 in the impulse mechanism, which permits further reduction of the impulse duration, and also in the construction of the pendulum, which is convertible from mean solar to sidereal time by a simple shifting of a special weight from the lower platform to the upper. Furthermore, work is being done on the design of an impulse mechanism with electromagnetic pulses for AChF clocks.

AChF clocks can be used widely in equipping astronomical observatories and laboratories of the time service. In addition, in conjunction with a quartz clock, they can be used for observations of the variations of gravity.

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