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A NEW TIME STANDARD

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A New Time Standard

By Henry E. Warren

Research by many individuals since the beginning of the century has added two new instruments for time measurement to the generally accepted pendulum clock. All of these are based, of course, on the primary astronomical standard which involves the revolution of the earth on its axis.

The oldest of these secondary time standards, the pendulum clock, has been perfected to such an extent that in the form of the so-called Shortt free pendulum, any error can be discovered only with great difficulty. Consequently, this device has come to be over the past decade the accepted standard for certain important purposes. The time signals which are sent out for use by navigators and scientists are generally derived from free pendulum clocks maintained with utmost care in government laboratories. The time keeping precision of these clocks is said to be of the order of one part in thirty million or about a second a year.

The next most precise standard, namely the vibrating quartz crystal which is universally used for the control of radio frequency and also for certain kinds of time service has a precision which is said to exceed one part in five million over a considerable period of time. However, this type of standard, if used for the measurement of time as distinguished from radio frequency, is very expensive and complicated and requires expert supervision. As many as ten or more vacuum tubes are needed to reduce the frequency of the quartz crystal to the standard 50 or 60 cycles of our power systems. Obviously continuity of service with such a large number of vacuum tubes, each having a limited life, might be somewhat troublesome.

The third time standard in fairly common use has a very special form of tuning fork preferably maintained in vibration by vacuum tubes. Standards of this kind are said to operate with a precision of one part in a million, which would correspond with an error less than one-tenth of a second per day.

The effect of variations in temperature on these time standards may be detrimental and therefore it is customary to maintain them at a very constant temperature. Consequently compensating means are usually provided for the purpose of minimizing temperature effect.

Several years ago the writer, who has been concerned with problems of speed and frequency regulation that are of course based on time measurements, determined to build if possible a more simple form of secondary time standard which would be free from some of the objectionable features of the very accurate devices commonly used. Utilizing the vibrations of a stretched string or wire seemed to offer attractive possibilities. Every one knows that a piano or violin string gives out a fairly constant musical note when set in vibration. It is evident, however, that the note depends on the tension of the wire and that it would be very difficult indeed to provide absolutely constant tension through the usual form of mounting. The very fact that frequent tuning is necessary makes this clear.

The force of gravity as a means of providing tension appeared desirable. Experiments at first took the form of a vertical wire stretched over two bridges and tensioned by a weight. If the distance between the two bridges could be held exact it appeared as though such a wire should have a very constant rate of vibration. The accuracy of this arrangement was only fairly satisfactory for several reasons. These were

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irregular pressure on the wire over the bridges, absorption of a portion of the vibrating energy by the structure which held the bridges, a tendency of the wire to vibrate in different modes, etc.

Gradually the device evolved into the form of a vertical wire or strip supported rigidly at its upper end and tensioned by a weight at its lower end. This was set into vibration by a force supplied at its central point so that when vibrating it consisted of a single loop with nodes at both ends. Many methods of imparting vibrations were tried but eventually a very simple vacuum tube coupling was adopted which supplied energy through the medium of a permanent bar magnet that also constituted loading at the middle point of the stretched wire.

In order to compel vibration in a definite plane the vibrating element at first consisted of a narrow strip of metal which was stiff edgewise, but later it was found that a round wire would vibrate in a plane provided the driving magnet was accurately centered.

There are numerous difficulties in a device of this kind. In the first place more than one mode of vibration may be established, for the wire can obviously vibrate in sections and it can also vibrate axially. Very soon it was discovered that if there was a fairly close correspondence between the normal rate of axial vibration of the system as a whole, including the weight, and one or more harmonics of the transverse vibration, the performance was wholly unsatisfactory. This meant that it was necessary to avoid certain proportions which involved frequency, length, and loading of the wire. Then it was found that a plain stretched wire or strip mounted in the manner described gave a frequency which increasedrather rapidly with the amplitude of vibration so that in order to maintain a definite rate it would be necessary to maintain a very constant amplitude.

The effect of temperature on the vibrating wire arranged in this manner is rather complicated. Variations in length due to this cause need not be troublesome because the wire can be made of a material like Invar which has a nearly constant length over a wide range in temperature, but the effect of temperature on the modulus of elasticity of the vibrating materials is an important factor. A vertical wire tensioned by a weight has elastic stiffness in a transverse direction, that is to say, it behaves somewhat like a beam fixed at both ends vibrating under a load at its middle point. The transverse elastic stiffness has the effect of increasing the frequency of vibration beyond that caused by the tensioning weight. The elastic stiffness at a given temperature varies very rapidly in inverse proportion to the fourth power of the diameter of the wire and in direct proportion to the cube of its length.

Common materials which might be used for this purpose like steel, brass, tungsten, beryllium alloys, etc., become less stiff, that is to say, their modulus of elasticity decreases with increasing temperature. Consequently, vibrating wires made from these materials will have decreasing frequency as the temperature rises. Fortunately there are certain materials, especially nickel steel alloys having composition very similar to Invar, that grow more stiff with increasing temperature. Vibrating wires made from this kind of material will show an increase in frequency as the temperature rises. The temperature coefficient of the elastic modulus of Invar is especially high, being in the neighborhood of 500 parts per million per degree centigrade. The temperature coefficient of the modulus of elasticity in the opposite direction of some of the other materials mentioned is much less, although still many times greater than the temperature coefficient of the length expansion.

It is possible to control the magnitude of the effect which temperature will have on the frequency for a given kind of material by planning the proportions of length, diameter, and loading of the vibrating wire. The smaller the diameter and the greater the length the less will be the effect of temperature changes which influence the elasticity of the material. For convenient lengths however, and with reasonable loading within the elastic limit of the material used, there will usually remain frequency variations when there are temperature changes. However, these variations may be made as small as desired if advantage is taken of the opposite sign of the temperature coefficient of the elastic modulus by making the vibrating wire in part of a substance like Invar having a temperature coefficient which gives greater stiffness with rising temperature and in part of another material like beryllium copper which becomes less stiff with rising temperature. If the relative lengths of these two materials are properly chosen the temperature effect of one may be made to cancel the temperature effect of the other as regards stiffness and if there is a slight residual of length expansion that may also be neutralized by a preponderance of one kind of elastic alteration.

There are alloys like Elinvar which have a nearly constant modulus of elasticity with regard to temperature but in the experiments which have been made with this kind of material the reduction of temperature effects has been less satisfactory than by the very simple method of combining materials which have opposite signs of elastic temperature coefficients.

Further means of eliminating any slight residual temperature effect may act by opposing or adding to the gravity force of the weight by an adjustable element such as a weak spring or a thermo-sensitive magnet which will aid or oppose the tensioning force as the temperature changes.

Variations in rate caused by changes in amplitude can be corrected in a very simple manner. The normal increase in rate with increase in amplitude results because the vibrating wire is comparatively rigid axially so that it forms a connection having a nearly fixed length between the weight and the upper support. The weight has very considerable inertia and it tends to remain at rest in a position where the average force which it exerts on the vibrating wire is constant but the instantaneous force varies. The relationship is obviously slightly different for each amount of amplitude.

The instantaneous effect of the force exerted by the weight results in a component at the center of the vibrating wire tending to restore it to tis mid-position and this component of gravity force is proportional to the tangent of the angle of deflection of the vibrating wire. If the component of force which is designated as restoring force were exactly proportional to the displacement of the wire there would be harmonic motion and isochronism. Then there might be no change in rate with change in amplitude.

However, because of the inertia of the weight and slight axial elasticity of the wire the instantaneous component of force varies in a different manner, being larger than the tangent of the angle for large angles of deviation and less than the tangent for very small angles. For this reason the frequency rate increases with the amplitude of vibration. In the case of an ordinary clock pendulum the reverse is true. There the rate decreases with increase of amplitude.

It has been found that if an elastic connection be interposed between the weight and the lower end of the vibrating wire the component of gravity force which tends to restore the wire to its mid-position more nearly approximates proportionality to the tangent of the deflection angle and if this elastic coupling between the weight and the wire is sufficiently soft the wire will actually vibrate with a slower rate as the amplitude increases.

These facts have resulted in the design of a vibrating element which consists in part of a member that is comparatively stiff in an axial direction corresponding to the wire (A) in Fig.1, and another member an elliptic spring (B) which is decidedly elastic in the same direction. The wire, however, is free to vibrate transversely while the spring is comparatively rigid in that direction.

A good result can be obtained by the use of other types of springs. For example the vibrating wire may consist of an upper portion flexible transversely and stiff axially with the lower portion in the form of a spiral spring which is flexible in both directions. The main desideratum is that the elastic flexibility of the spring member in a vertical direction shall have that scale of stiffness which insures that the frequency rate of transverse vibration of the vertical element will be approximately the same over a reasonable range in amplitude.

While it might be possible to compute the exact dimensions of the elements that are involved in the combination the problem would be a very complicated one, but it is fairly easy to find the correct proportions by experiment. Fig. 2, shows several curves which illustrate the relation between amplitude and rate of a certain vibrating wire when coupled to the tensioning weight by elliptic springs of different lengths. These curves indicate very clearly that with the correct stiffness of elliptical spring the rate of the vibrating wire scarcely changes over a fairly wide range in amplitude.

Various methods of driving the vibrating wire have been tried, all of which involve some form of coupling between the wire and a vacuum tube circuit. One very satisfactory form consists as shown in Fig. 1 of a small permanent bar magnet of cobalt steel very rigidly attached at the center of the wire. One end of this magnet projects into a pick-up coil and the other end is surrounded by a driving coil. These two coils are connected respectively to one grid and plate of a twin triode tube.

The other half of the tube is used for amplifying the voltage of the first stage. In order to avoid picking up external frequency in the first stage a 22 1/2 volt plate battery is used. The heater current and the other plate supply voltage come from a regular power circuit. A second tube further amplifies the energy so as to deliver about two watts at 120 volts which is adequate to operate a Telechron clock motor. For greater power a small amount of this output is diverted to another stage of amplification.

The relation between the plate battery voltage and the time rate in seconds per day is shown in Fig. 3. The amount of current drawn from the plate battery is less than a tenth of a milliampere so that reduction of battery voltage takes place very slowly indeed. The amount of energy required to keep the string in vibration at ordinary atmospheric pressure is less than half a milliwatt.

The effect on the rate of barometric changes in the atmosphere is extremely small; apparently less than a tenth of a second per day for the ordinary range. Therefore it does not seem necessary for most purposes to provide an air-tight enclosure for this time standard but the instrument is so constructed that a bell jar can be placed over it. The compensation for variations in temperature is so accurate that for most purposes temperature control is unnecessary.

The instrument can be constructed so that 100°F. difference in temperature will produce less than one second per day variation in rate. Where the surrounding temperature is not likely to vary more than 10°F. the error due to this cause is negligible for many purposes. Probably the best location for an instrument of this kind is on a foundation of its own in an underground enclosure where the temperature would be comparatively constant.

For the purpose of measuring the progress which has been made in reducing temperature effects one of these compensated time standards has been exposed to comparatively wide temperature variations for a period of ten days. This was done by subjecting it to rather high room temperature during working hours and then cooling the room at night by shutting off the steam heat and opening the windows to the outside New England air. The twenty-four hour average temperature varied from 65°F. to 81°F. and intermediate changes as great as 40°F. were observed. Over this period the average rate was one-tenth second per day fast. The greatest error was four-tenths of a second per day. No attempt has yet been made to determine the extreme precision which can be obtained with this new instrument but the indications are that time can be measured with an error less than one-tenth second per day when favorable conditions are provided.

There is an additional feature of this new time standard which may be of great importance for certain purposes. The weight which tensions the vibrating wire and very definitely controls its frequency is of course constant under the influence of gravity. Forming a part of this weight is a cylindrical Alnico magnet and in the air gap of this magnet there is a coil of fine insulated wire.

When a measured direct current is passed through the coil the reaction between the magnetic flux and this current will produce a force in the same direction as the gravity force but plus or minus in sign depending upon the direction of the current. The value of this current may be accurately adjusted by a graduated potentiometer or resistance so that the frequency rate of the vibrating wire may be controlled with great precision over a moderate range from a distant point. Fig. 5 shows the relation between frequency and control current.

The amount of energy necessary to adjust the rate of a 60 cycle time standard over a range of plus or minus one cycle by this magnetic method is less than one-tenth of a watt. Consequently, there are no important heating effects which might be disturbing and the control apparatus may be very simple.

In order to study the performance of these new time standards an interesting form of graphic comparator illustrated in Fig. 6 has been constructed. This consists essentially of a long revolving screw arranged transversely with respect to a moving strip chart. The screw is driven through gearing from a Telechron synchronous motor. On the screw there is a nut carrying a gear which is made to rotate by another Telechron motor. The gear reduction from this second motor to the nut is such that the screw and the nut normally revolve at the same speed and in the same direction. Any axial motion of the nut is transmitted to a light slider which carries a pen making contact with the paper chart.

Thus the line drawn by the pen indicates the axial position of the nut at any instant. One of the two synchronous motors is connected to a standard source of frequency and the other to a source of frequency being studied. This can for example be a power system in which case the line drawn on the paper chart will be an accurate record of the integrated system frequency. A small section of such a chart is shown in Fig. 7 curve Q. This record was made on one of the big eastern power systems and shows on a very open scale the integrated speed fluctuations which are continually taking place. In this particular chart the fine graduations are one-fifth of a second or 12 cycles apart. Consequently, it is possible to read extremely small frequency errors with high precision, far exceeding any of the ordinary graphic frequency recorders.

The slope of the curve is a measure of the instantaneous frequency. The transverse lines in this particular record are one hour apart. Consequently, a frequency error of 1/100 of a cycle corresponds with a time error of six-tenths of a second per hour or an angle of about 45°. An error in frequency considerably less than 1/1000 of a cycle can easily be seen. The kind of speed regulation on a system whether by ordinary governors supplemented by manual adjustment or by some type of automatic frequency controller, will determine the form of curve Q so that considerable information may be obtained from this record.

Fig. 7 curve S which is made by comparing one of these new time standards running at fixed temperature with another operating at variable temperature shows very clearly the high precision of the instruments. The temperature variations to which the second instrument was subjected are shown in curve T. It is interesting to compare curve Q with curve S and observe how far short of perfection system frequency is at the present time although for most commercial purposes it is very satisfactory.

For certain requirements precisely controlled frequency of this kind may be very important. For example, in driving large telescopes in astronomical observatories it is necessary that the image of a star or other heavenly body should be held stationary in the field of the telescope for the purpose of making photographs which sometimes require hours of exposure. Since the telescope is swinging about an axis parallel to that of the earth one might suppose that the rate of angular motion should be exactly uniform to follow a star. Actually, it is necessary to vary this motion slightly because the refraction by the earth's atmosphere increases steadily from the zenith to the horizon.

Obviously, one of the best means of driving a telescope is a synchronous motor but if such a motor is supplied with alternating current of perfectly constant frequency some mechanical means is needed to adjust for the slight apparent error in stellar motion. The difference in motion of other heavenly bodies such as a planet or the moon would of course require a much greater adjustment of the rate.

From this explanation it will be appreciated that this new time standard contains within itself means for extremely precise and easily controlled rate adjustment and that it can supply alternating current to a synchronous motor driving a telescope so that the latter will accurately follow the motion of a heavenly body. The method of adjustment in the case of a star where the rate varies from the zenith to the horizon may become automatic through the use of suitable cams. Thus after the telescope has once been focused on a star the image will remain stationary in the telescopic field without any manipulation by the observer.

Utilization of this instrument for the purpose of driving telescopes is only one of a great many possible applications. To the scientist and engineer it may prove another useful implement in the endless campaign of progress.

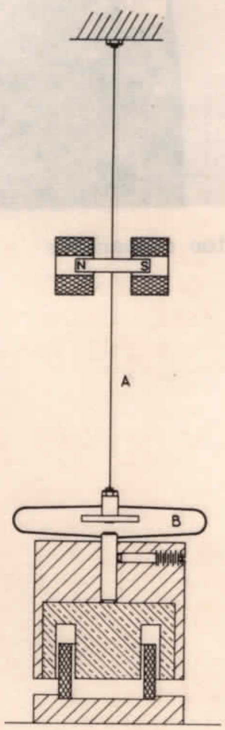

Fig. 1-Diagrammatic representation of vibrator assembly in section

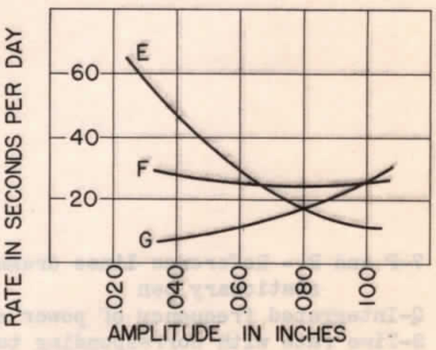

Fig.2-Rate compensation for changes in amplitude by means of a resilient bow

E-Over compensated-bow length 2.82inches
F-Full compensated effect-bow length 2.50inches
G-Under compensated-bow length 2.27inches

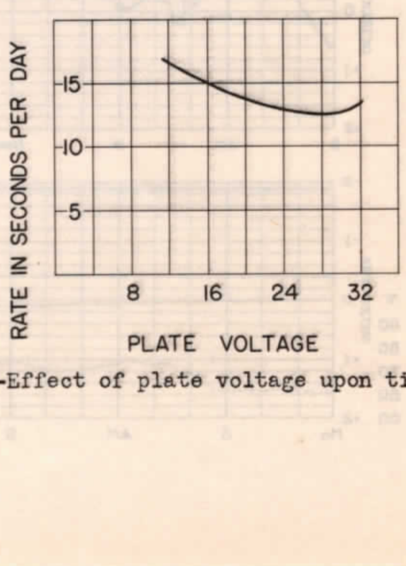

Fig. 3-Effect of plate voltage upon time rate

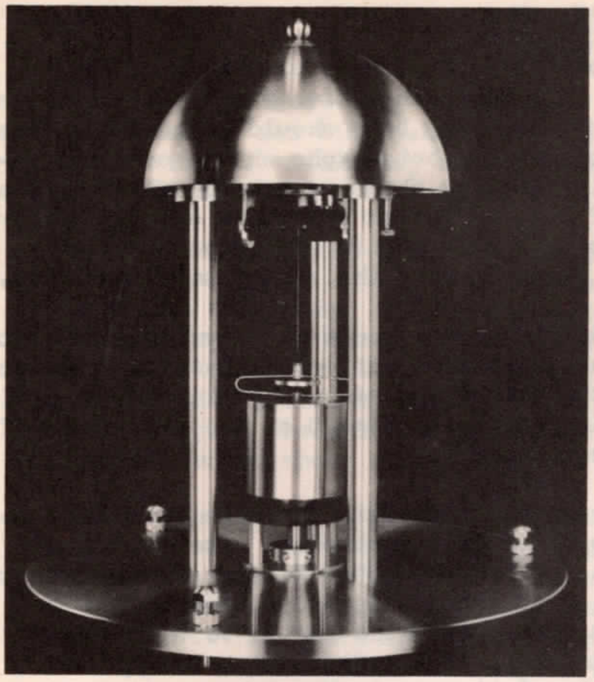

Fig. 4-Complete vibrator unit
Diameter of base 14 inches

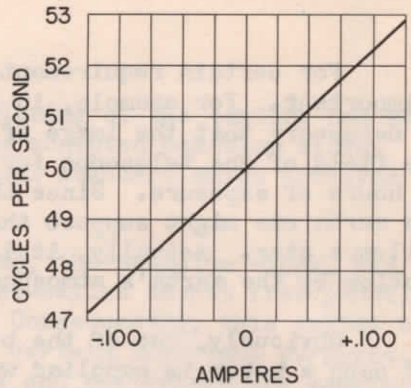

Fig.5-Relation between current in regulating coil and frequency

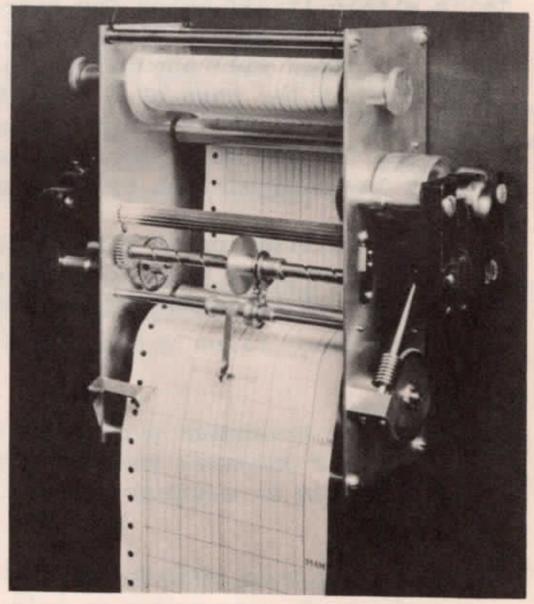

Fig. 6-Graphic time comparator

Fig. 7-P and R - Reference lines drawn by stationary pen
Q-Integrated frequency of power system
S-Time rate with corresponding temperature variation T of vibrator unit