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On the Superiority of Zinc and Steel Pendulums.

By Thomas Buckney.

At the last meeting of the Royal Astronomical Society, Dr. Leonard Waldo, of Yale College, U.S.A., was good enough to give us an account of certain improvements in astronomical clocks, or, as he preferred to call them, "clocks of precision." The net result of these improvements was stated to be a reduction of about 25 per cent. in the average errors of clock rates, and this as compared with the best previously existing clocks. This, if substantiated, would be a most important gain; but, unfortunately, Dr. Waldo gave us no figures in support of his statement, which, therefore, goes for nothing more than a mere expression of his own individual opinion. Now I cannot help thinking that when a statement of this kind is made to such a Society as this, it ought, to have any value, to be accompanied by the data on which it is founded, so that anyone interested in the matter may be able to weigh the facts and verify the deductions made from them. In the absence of such data we can only discuss the methods adopted, and endeavour to satisfy our own minds that they would probably produce the result said to be attained.

Now, the Yale clock or clocks which appear to have been constructed under Dr. Waldo's direction embody the following features, and it is to them that he attributes their excellent performance. They have:

1st. A heavy mercurial pendulum, the mercury weighing from 45 to 60 lbs. The jars containing the mercury and the pendulum rods are of steel.

2nd. The suspension of the pendulum is on a knife-edge, in lieu of the spring commonly used.

3rd. The escapement is a modification which is stated to be an improvement of one of the forms of Denison's Gravity Escapement.

4th. The support of the pendulum is a massive iron arch spanning two piers of masonry similar to the piers of a transit instrument, and it is between these piers that the pendulum swings. The clock movement is supported on a bracket placed between the piers, around which some arrangement of steam pipes is introduced for the purpose of regulating the temperature.

Well, now, the first thing that crosses one's mind is that some of these improvements are old acquaintances. Let us see, therefore, what is known about them, taking each one in the order already given. In order not to weary you I will, if possible, confine my references to one little book, which, although it has run through several editions and was written by a gentleman who is a Fellow of this Society, Dr. Waldo must, I think, imagine that few of us have seen. Perhaps Dr. Waldo himself has not seen it, in which case I commend it to his notice, as the author, who is President of the British Horological Institute, is generally recognised as an authority on these matters. It is entitled "A Rudimentary Treatise on Clocks, Watches, and Bells," and I refer to it to prove that heavy mercurial pendulums, such as Dr. Waldo recommends, have been in use for many years. For in an edition of the work published in 1874 the author says, "In 1863 I had to calculate the height (that is, of the mercury) for the iron jar of a pendulum intended to weigh 40 lbs." Besides, there is on the Water Clock used for driving the Greenwich Equatorial, a mercurial pendulum of about this weight, which was made by my own predecessors probably thirty years ago. The jars of these pendulums were of iron it is true, but this is a point which is absolutely immaterial.

Now as to the knife-edge suspension. In a still older edition of this same rudimentary treatise—one published in 1850—I find it stated, "Occasional mention may be seen in books of pendulums vibrating for several hours on knife-edges—that is, on a suspension much like that of a scale beam. Such a suspension is the best for experiments to ascertain the undisturbed time of vibration due to gravity only, excluding the elasticity of a spring; but it is not to be inferred that it will answer in practice for a permanent pendulum of the proper weight for a clock, for even if the knife-edges and the planes on which they stand are made of the hardest stones, it is found that they soon suffer from the severe pressure, and introduce an amount of friction which is fatal to the accuracy of the pendulum." Well, since this condemnation, as far as I am aware, as regards clocks, the knife-edge suspension has remained dead and buried until Dr. Waldo dug it up and brought it as treasure-trove to our last meeting.

The modification made at Yale in the gravity escapement may or may not be an improvement. In either case it can have very little effect on the time-keeping of the clock, as it affects only the lifting of the arms by the clock train. As far as the pendulum, which is the time-measurer, is concerned, the escapement remains precisely what it was before the alteration.

I quite agree with the importance Dr. Waldo assigns to a rigid support for the pendulum. And here we are perfectly in accord with the author of the "Rudimentary Treatise," who points out its advantages in every edition of his work. There is a simpler and probably a better way of obtaining the desired rigidity—that is, by bolting a massive iron bracket to one of the main walls of the building in which the clock is to be placed, and hanging the pendulum from that; but it is obviously immaterial in which way the desired rigidity is obtained so that it be really secured. We now come to the last of Dr. Waldo's improvements—the introduction of steam piping round the piers on which his clock is fixed; and this certainly is a novel proposal. I will not, however, say any more about it, as I hope to be able to show that it is, or ought to be, quite unnecessary. But my purpose in the present paper is not so much to show the antiquity of the novelties brought before us by Dr. Waldo as to show that they are not well calculated to yield the result he claims for them; and this more particularly applies to the pendulum, to which, as the time-measurer, I propose to confine myself. As it is possible that in what I am about to say I may repeat something I said at the last meeting, I must ask you to excuse me. Having had no idea that this subject was to be brought forward, I had no opportunity of referring to my memoranda bearing on it, and so was placed at a great disadvantage, as I had to speak entirely from memory. But the matter seems to me of sufficient importance to induce me to trespass on your time this evening, as I should be sorry to find Dr. Waldo's paper accepted as an accurate description of our knowledge as regards astronomical clocks.

Well, about eighteen years ago, it fell to my lot to make designs for four astronomical clocks, one of which was destined to become the sidereal standard clock of the Greenwich Observatory; the others were to be used as transit clocks in the British Transit of *Venus* Expeditions. The first of these clocks was by far the most important, and was to be constructed so as to embody the features of a specification drawn up by Sir George Airy. But the only point we have to consider here is the pendulum; which was to be a mercurial one. The other clocks were fitted with zinc and steel compensation pendulums, constructed in what was then the ordinary way; that is, the bobs, which were cylinders of lead, were supported at one end, so that the expansion or contraction of the bob itself entered into the compensation. These four clocks, completed at about the same time, were set going in a quiet room, in which there was a gas-stove, by which the temperature could be raised without difficulty to 90°. As set going under these circumstances, these clocks had a rather considerable temperature error; but what seemed at first rather curious was that this did not at first show itself in a very marked way, but kept on increasing for two or three days until the clocks finally settled down to a steady rate due to the higher temperature, and a similar sluggish action was noticed when the temperature was allowed to run down. It became evident that this sluggish action was due to the more slender parts of the pendulum (the rods and spring) taking up the new temperature very quickly, whilst the bobs, being much more bulky, required a much longer time to do this. I would here mention that, fully recognising the advantage of a heavy pendulum, I had given the Greenwich clock a jar $2\frac{3}{4}$ inches internal diameter, holding about 20 lbs. of mercury, the diameter of the jars in ordinary use being 2 inches, which would hold about 12 lbs. of mercury. Considering the matter, it occurred to me that if we were to eliminate from the compensative action of the zinc and steel pendulums the expansion of the bob, which we could easily do by suspending it at its centre of gravity, and rely entirely on the zinc and steel tubes and rod, matters would be very much improved, as then the compensation would be effected by parts having pretty much the same bulk, and therefore likely to act simultaneously. And so it turned out. These zinc and steel pendulums were reconstructed on the principle above indicated, and the clock rates became very soon all that could be wished. But the Greenwich clock could not be altered in this way, as in a mercurial pendulum the compensation is and must be effected entirely by the expansion of the bob, and there seemed no satisfactory way of increasing the rapidity of its action whilst maintaining its weight. In the end I determined to lay the matter before Sir George Airy, and request his sanction to the removal of the mercurial pendulum from the Greenwich clock, and the substitution in its place of a zinc and steel pendulum on the new principle. The change produced the same rapid and simultaneous action obtained in the other clocks, and has, I venture to think, been quite satisfactory. It was in this way that it came about that the Greenwich clock has a zinc and steel pendulum, instead of the mercurial one originally intended for it.

Some time after this, being desirous of investigating more fully this sluggish action of the mercurial pendulum, I made the two following experiments, which are rather interesting. I took an ordinary mercurial pendulum jar of two inches diameter, and, having removed the steel rod, I cemented in its place a glass tube and filled the top completely with mercury, and also the tube to about half of its height. I marked the height of the mercury in the tube, and noted the temperature, which was about 60°. I then plunged the pendulum into hot water—temperature about 150°—and the result was as follows:

Almost immediately the mercury sunk in the tube considerably, but in less than a minute it began to expand with the heat, and then rose rapidly. The first effect of a sudden rise in the temperature was, however, to make the mercury fall—a phenomenon due evidently to the expansion of the jar by the sudden rise of temperature taking place before this new temperature was felt by the mercury to a sufficient extent to counteract it. This experiment, which was repeated several times with the same result, shows that the first effect of a change of temperature on a mercurial pendulum is in the inverse direction, and aggravates the error it is intended to correct. This goes on, although gradually lessening, until the mercury acquires the new temperature. But before this happens, an error has arisen which cannot be corrected; it may be, however, and probably is in many instances, masked by over-compensation. In any case irregularities of rate are engendered.

The next experiment was made as follows:

Two mercurial pendulum jars were taken, one of 2 inches diameter, and the other $2\frac{3}{4}$ inches diameter, the latter being the one discarded from the Greenwich clock. These were filled with mercury to about the height that would be required to compensate the pendulums. In the place of the pendulum rods thermometers were inserted, the bulbs of which were plunged into the centre of the mercury and so arranged as to project above the caps of the jars to such a height as to allow the temperature to be read off. Similarly, a short length of the outer steel tube of a zinc and steel pendulum was taken, the lower end being stopped by a cork. Inside this was placed a short length of the zinc tube, and inside this, in lieu of the steel rod, was a thermometer as in the mercurial jars. A large saucepan was then obtained from the kitchen, and having adjusted the bobs and compensating piece of zinc and steel on a piece of non-conducting material in the bottom of the saucepan, water was put in until it nearly reached the top of the bobs. The saucepan was then placed on a gas-stove and the temperature raised to about 200°, and the whole kept in this state for a couple of hours, by which time the high temperature had thoroughly pervaded the masses of metal, as was shown by the readings of the thermometers. The bobs were then removed from the water and placed at a certain distance apart in a quiet room, the temperature of which was about 60°. Now, the object of this experiment was to ascertain how long each of these pendulums took to adapt itself to a new temperature; and the three thermometers were therefore watched, and the time each one took to cool down a certain number of degrees was noted.

Well, then, to cool down from 180° to 140° the zinc and steel pendulum took 4 minutes; the 2-inch mercurial one 21 minutes, and the $2\frac{3}{4}$-inch mercurial $29\frac{1}{2}$ minutes. To cool from 140° to 120° the times occupied were respectively 5, 15, and $22\frac{1}{2}$ minutes; from 120° to 100°, 8, 24, and 38 minutes; from 100° to 90°, 5, 19, and 29 minutes; from 90° to 80°, $8\frac{1}{2}$, 28, and 49 minutes; and from 80° to 70°, below which point the observations were not carried, the times were $26\frac{1}{2}$, 70, and 115 minutes. And the times respectively over the whole range of the experiment—that is, from 180° to 70°—were 57, 177, and 283 minutes.

The importance of these results will be more apparent and better appreciated if arranged in a table, as follows:

Temperature.	180° to 140°	140° to 120°	120° to 100°	100° to 90°	90° to 80°	80° to 70°	180° to 70°	Ratios
Zinc and Steel	4	5	8	5	$8\frac{1}{2}$	$26\frac{1}{2}$	37	1
2-inch Mercurial	21	15	24	19	28	70	177	3
$2\frac{3}{4}$-inch Mercurial	$29\frac{1}{2}$	$22\frac{1}{2}$	38	29	49	115	283	5

Now, this experiment, to my mind, shows clearly that in any given change of temperature a zinc and steel pendulum in the compensating action of which the bob has no share is three times as rapid as a mercurial pendulum with a 2-inch jar, and five times as rapid as one with a $2\frac{3}{4}$-inch jar, and the clock errors would be in the proportion indicated by these figures. Indeed, it is certain that the zinc and steel pendulum would in practice show even better than it did here; because in these pendulums the steel tube is cut through so as to expose nearly the whole of the zinc tube, and this latter is pierced with many holes to allow the temperature to reach the inner rod, whereas in this experiment the tubes were entire. As regards the two mercurial pendulums, it will be seen, as might have been suspected, that the larger one took longer to cool than the smaller, although possibly one would not have thought that the difference would be so great. It seems to vary rather more quickly than the area, but this may be due to some difference in the thickness of the walls of the two jars. Let us, therefore, assume that the sluggishness varies as the area, and see how the large bobs containing 45 and 60 lbs. of mercury, recommended by Dr. Waldo, would come out. These would have an internal diameter of four and five inches approximately, and the areas would be as follows:

Diameter	2	2¾	4	5
Areas	3·14	5·93	12·56	19·63

If, therefore, my experiment holds good for these larger diameters (and I do not see why it should not do so), Dr. Waldo would find that his 4-inch pendulum would take 12½ times as long as the zinc and steel one, and his 5-inch pendulum 20 times as long, to adapt themselves to a new temperature, and as compared with the 2-inch pendulum in common use they would be 4 and 6½ times as long. And it will be evident that the more the size of the jar is increased the greater the error will be. In fact, of mercurial pendulums it may be said the bigger they are the worse they are. The errors of Dr. Waldo's clocks, due to the sluggish action of his large pendulums, may, no doubt, be lessened by a careful manipulation of his steam pipes; but clocks cannot always be treated as exotics: we want something more hardy. I would urge most strenuously the importance of protecting clocks from sudden and great changes of temperature. It is, indeed, absolutely necessary that this should be done, and if a dry underground chamber can be found and a clock set up in such a place, where only gradual variations of temperature occur, one may reasonably look for a good performance. But such protection cannot always be found, and in order to prove that a zinc and steel pendulum can, and does, give a good result under very trying circumstances, I cannot do better than append the following rates of one of the three clocks referred to in the earlier part of this paper. These rates were taken for a period of six months, from September 3, 1871, to March 21, 1872, during which time the clock was going in one of the little huts prepared for the Transit of *Venus* Expedition, erected in the grounds of the Royal Observatory, and are extracted from the official records of that Institution.

Royal Observatory, Greenwich.

Errors and Rates of the Clock "Dent" 1914, *on Greenwich Sidereal Time.*

Date.				Clock slow.		Mean daily losing rate during each interval.	Average temperature of external air.	Extremes of temperature of external air.
		d	h	m	s	s	°	° °
1871	Sept.	3	21·7	14	31·8	4·45	61	79−47
		17	21·5	15	34·1	4·02	52	68−39
		24	21·8	16	2·3	4·54	51	66−42
	Oct.	1	22·6	16	34·2	4·43	51	65−40
		8	21·9	17	5·1	4·55	46	60−31
		15	21·6	17	36·9	4·47	54	68−41
		22	21·6	18	8·2	4·24	47	59−33
		29	21·3	18	37·8	4·25	46	55−35
	Nov.	5	22·7	19	7·8	4·07	38	50−26
		12	22·2	19	36·2	4·24	35	51−20
		19	21·7	20	5·8	4·36	36	44−28
		26	21·7	20	36·3	4·33	36	43−28
	Dec.	3	22·2	21	6·7	3·89	30	40−19
		10	21·9	21	33·9	4·67	41	47−27
		17	21·8	22	6·6	4·77	42	49−35
		26	0·1	22	45·2	4·74	43	48−33
		31	21·9	23	13·2	4·72	42	51−34
1872	Jan.	7	22·3	23	46·3	4·93	40	51−32
		14	21·6	24	20·7	4·79	39	48−28
		21	21·6	24	54·2	5·13	42	51−36
		28	22·1	25	30·2	5·17	45	54−37
	Feb.	4	22·1	26	6·4	5·00	47	58−33
		11	22·2	26	41·4	4·96	44	54−37
		18	21·7	27	16·0	4·85	45	56−35
		25	21·8	27	50·0	4·88	46	58−32
	Mar.	3	21·6	28	24·1	4·86	47	61−28
		10	21·6	28	58:1	4·73	46	59−28
		17	21·4	29	31·2			

During the whole time of rating, the clock was situated in one of the small Observatories intended for use in the observations of the Transit of *Venus*, 1874. No record of the temperature of the hut was kept, but its temperature would be nearly the same as that of the external air.

But our experience of these zinc and steel pendulums is not limited to these four clocks. There are three in use in the Royal Observatory, Greenwich, and others fitted with these pendulums will be found at the Observatories of Brussels, Liège, Copenhagen, San Fernando, Coimbra, Lisbon, Tokio, Hongkong, Cape of Good Hope, Port Elizabeth, and at many others; but these will suffice to show that they really do work well. A further improvement has recently been introduced, which allows an alteration in the compensation to be made by the astronomer without the slightest difficulty, and this without making a very wide difference in the clocks' rate; thus removing the possible objection that such an alteration could only be made by a clockmaker. I hope to bring this before you at some future time. As it is, I fear I have already detained you much too long. But I wished to show you that Dr. Waldo's novelties are not new, and that they are not likely to realise his expectations. I wished to point out the defects of the large mercurial pendulums he recommends; and I hope I have made it clear that, in a variable temperature, these pendulums do not and cannot act with the rapidity that is necessary. In order to maintain a steady rate, it is essential that the length of the pendulum—that is, the distance between the point of suspension and the centre of oscillation—shall, under all circumstances, be unaltered; a result which cannot be obtained with a pendulum, one part of which is affected by a change of temperature before the other part. If, then, my experiments are to be relied on, the conclusion must be drawn that the zinc and steel pendulum much more nearly fulfils the condition of simultaneous action, and is for this reason to be preferred. And this conclusion is justified by actual experience.

Ephemerides of the Satellites of Saturn, 1886–87. By A. Marth.

The five inner satellites deviate so little from the plane of the ring that their deviations are most suitably treated as latitudes above this plane, the ascending node N and inclination I of which, in reference to the plane of the Earth's equator, are here assumed to be

$$\text{for } 1887{\cdot}0 \qquad N = 126^\circ{\cdot}5896 \qquad I = 6^\circ{\cdot}9973$$

The assumed longitudes of the five satellites in their orbits (i.e. their longitudes from the ascending node added to the Right Ascension N of the ascending node, reckoned from the point of the true equinox), referred to the time when the light arrives at the distance [0·950], are the following:

M M 2