Harrison’s Barometric Compensation
Keeping it Simple: A Description from Practice

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Introduction

The last few years have seen considerable excitement, and some controversy, over the astonishingly successful trials of Burgess Clock B at the Observatory. In association with this work, there have been a number of published articles, including one last year in which we at the Observatory narrated the main facts surrounding the trials of Clock B [Ref.1: ‘A Second in 100 Days – The Result’ Rory McEvoy, Horological Journal, September 2015, pp 407-410].

Other published papers have provided theories as to how Harrison’s system might work, giving lots of historical context to those theories, [Ref: 2. ‘The Harrison Hill Test’, M.K.Hobden, HSN 2012-5 et Seq.; 3. ‘Dominion and Dynamic Stability’, M.K. Hobden, HSN 2015-4, pp 9-19; and 4. ‘Investigating the Harrison Pendulum Oscillator’, John Haine & Andrew Millington, HSN2016-3] and in this issue John Haine and Andrew Millington continue their commentary on Harrison’s pendulum oscillator and provide a theoretical model for how the barometric compensation system works.

Adjusting a Harrison Clock

As is now well known, adjusting a Harrison-type pendulum clock for optimum performance, including introducing compensation for barometric pressure changes, involves carrying out a series of what has been termed ‘hill tests’. In discussing this work among horologists, it is clear that many are of the opinion that the whole business is exceedingly complicated and time consuming. To quote one commentator, adjusting a Harrison clock appears to involve “overwhelming time and effort in fine-tuning”.

This is simply not so, and as a complementary precursor to John and Andrew’s theoretical paper, I thought it might be useful to describe in simple terms, for the non-mathematicians, what was actually involved in the relevant ‘hill tests’ and adjustments to Clock B, to show how straightforward it really is.

Since the beginning of the trials of Clock B at Greenwich, there have been a number of remarks made in the horological community about the trials themselves and the implications for precision timekeeping, which require clarification. At the end of this article I would therefore like to take this opportunity of commenting on
some of these, perhaps to dispel a few myths which have grown up around these trials in recent years.

The First Trials

The first trials of Clock B were undertaken at Charles Frodsham’s who were entirely responsible for completing the movement after it left Martin Burgess’s workshop. At that point it only had the upper train, remontoire, escapement and pendulum, but no lower train or weight drive system. On completing the work and setting it going, it was immediately clear the clock would perform well. It was after these very encouraging tests that Frodsham’s recommended it came to Greenwich for independent verification of its capabilities in 2012, something the new owner of the clock – who has yet to receive it in his home – very generously agreed to.

The early tests at the Observatory, conducted by me, with colleague Rory McEvoy very skilfully overseeing the Microset monitoring equipment, recorded clock rate against temperature, barometric pressure and relative humidity. These early tests are described in the article in the Horological Journal (Ibid. Ref.1), and need not be repeated here. Suffice to say the clock, which had not, at that stage, been the subject of hill tests, nor adjusted for barometric compensation, nevertheless performed exceptionally well, and for one 110 day period in late 2012 / early 2013, showed an error consistently within one second of mean time for over 100 days of that period (See Figure 1).

Figure 1. The Microset record during the early trials (111 days shown) of Clock B in 2012/13. The traces are: light blue Amplitude; dark blue Error (‘Drift’, not Rate); pink Humidity; yellow Barometric Pressure; green Temperature.
The anomalous spikes in amplitude and one in humidity are artefacts of the recording system and do not represent any real physical activity.

The data showed the clock to be well compensated for temperature, but to be distinctly affected by changes in barometric pressure. It was only because the clock was carefully adjusted to have a zero rate at a mean barometric pressure, and that the barometric effects were ‘give and take’, that the clock was able to remain so close to mean time.

**The Hill Tests**

So, the time had come to adjust Clock B to introduce Harrison’s barometric compensation, which meant carrying out the hill tests.

For the less scientifically minded, it might be helpful to explain what happens to a pendulum when the pressure changes. In simple terms, two things happen. First and foremost with a rise in atmospheric pressure the pendulum experiences increased floatation effect, owing to its being suspended in air of greater density. Just as with a body suspended in water, it is buoyed up more and this effectively reduces the value of the restoring force gravity, so the pendulum tends to swing more slowly. Secondly, owing to the greater density of the air, the pendulum has more work to do in passing through it, and the greater energy consumed means that the arc of swing reduces. The amount it reduces depends on the shape and size of the pendulum and how quickly it changes will depend on the sheer mass of the pendulum. A very slippery and very heavy pendulum will not change its arc so much, nor so quickly, with a change in air density.

Because of circular deviation, minimising arc change might seem like a good thing, and traditionalists would say it is, all you need to do is to maximise the aerodynamics and the pendulum hardly changes its arc at all. However, whatever the shape of the pendulum, it will be subject to the first problem - floatation effect - which will always cause the pendulum to swing more slowly when the air density increases, unless you introduce some form of compensation. This is why traditionalists then fit some form of compensator, like an aneroid capsule, to correct for floatation.

Harrison looked at the problem in an entirely different and holistic way. He accepted that floatation effect is present, but recognised, indeed welcomed, the fact that the arc will also change owing to increased air density. Harrison’s pendulum system incorporates suspension cheeks, and having mostly removed circular deviation with them, he then deliberately re-introduced a measured amount of that
effect, specifically to counteract the floatation effect. For this reason, the Harrison system actually avoids a highly slippery pendulum, because it needs a significant change in arc with air density change, in order to get the correction from the cheeks.

It is important to state that the presence of Harrison’s recoil escapement also plays its part in the dynamics of this system, but in order to keep this explanation simple, the essence of the barometric compensation can be explained without going into that detail.

In order to introduce this barometric compensation, it is necessary to adjust the suspension and cheeks, so that, all other things being equal, there is a slight gaining tendency when the arc falls and this is where the hill test comes in, the term ‘hill’ referring to the shape of the curve on the graph which is produced during the test. What the ‘hill test’ does is simply to record the rate of the pendulum, in graphical form, at a variety of different arcs, on either side of an average, close to the running arc.

![Figure 2. A graph showing the rate of a clock (seconds per day) against the arc of the pendulum (shown here in terms of remontoire set-ups). This is the essential basis of a Hill Test.](image-url)
The graph in Figure 2 is not a real recording of any data, it just shows the kind of response which we are aiming at from the clock. In reality, what this graph shows is the right hand side of ‘the hill’. When starting the tests one does not necessarily see this side of the hill right away and adjustments to the cheeks and suspension are necessary, and the tests repeated, until ‘the hill’ appears on the graph.

In order to carry out the hill tests, one has to artificially change the amplitude of the pendulum in a very repeatable way, and to do this on a Harrison-type clock, one changes the ‘set-ups’ of the clock’s remontoire. The ‘set-ups’ are the individual increments by which the remontoire spring is tensioned. Each time the remontoire is released by the clock (which occurs every 30 seconds) it winds the spring back to the required tension. Rather like with a fusee, the remontoire spring has to be tensioned initially, and this determines the force with which the remontoire drives the clock. To pre-tension the remontoire one simply releases it the required number of times (each time being one ‘set-up’) in the same way the movement triggers it. With Burgess B, the running arc is maintained with the remontoire ‘set-up’ six times from completely relaxed. It is worth observing here that unlike Harrison’s design for the RAS remontoire (and as seen in H3) which employed constant-force helical remontoire springs, Burgess B has a flat spiral spring, which means the torque delivered will change slightly over every 30 second cycle, but this cycling should (and evidently does) repeat and should provide a constant drive in the longer term.

The remontoire set ups shown in the graph are four, five, six, seven and eight rewinds which is more than sufficient for the test. For the actual hill tests on Clock B, I even ran the clock rather further. With the remontoire at four rewinds the clock would barely run at its escaping arc of about 10½ degrees, and at ten rewinds the pendulum was running at the limits of the pendulum scale at over fifteen degrees. The test at various amplitudes has to be done quite quickly, to ensure that they are all carried out at the same barometric pressure. If the pressure changes significantly during the tests then the results will be flawed. Nevertheless, for each point on the graph it is only necessary that the clock is run up to its running arc and allowed to stabilise for a few minutes and one has the reading one needs, so its not a difficult or time consuming practice.

Once the adjustments (explained shortly) are complete, and a graph produced which shows a hill which is in the correct place, there will be an increasing gain at lower arcs of the pendulum. In this way, when the pendulum arc falls owing to a rise in air density, the losing tendency caused by the floatation effect is cancelled out by the gaining effect in the cheeks.
Constant impulse essential

Of course, the system depends on the arc of the pendulum only changing when the air density changes. If the pendulum arc changes for any other reason, such as a change in impulse, then the pendulum suspension will cause an unwanted change in rate, which is why Harrison was so concerned to make sure the impulse was constant with his remontoire, so the amplitude didn’t change for that reason.

Temperature changes air density too

A change in air temperature will also cause a change in the pendulum arc, caused by the changing air density with temperature. As with barometric pressure change, these variations are corrected automatically by the cheeks and suspension in the same way (Indeed, it might perhaps be better to name the concept ‘air density compensation’, rather than barometric compensation). However, it appears there is a further factor caused by temperature change, which is currently not fully understood, and which will be discussed briefly later.

The Adjustments

In arranging for the clock to gain in the smaller arcs, the pendulum and suspension are adjusted in two ways. First and foremost the suspension cheeks have to be cut to the optimum radius to put us in the right ballpark. This, Martin told us, had already been partly done when Clock A and B were under construction, but Frodsham’s machined the final radius on the cheeks of clock B during its completion. The second, somewhat more subtle means of adjustment is then to alter the thickness of the suspension spring. As Harrison said, it must be “…thin to the purpose”.

Changing the thickness of the suspension spring has a slightly counter-intuitive effect. The thicker the spring the greater the loss in the larger amplitudes. One might expect a thicker suspension spring to introduce a greater net gain into the system, but in conjunction with the cheeks, the thicker the suspension spring, the greater the relative loss in the higher amplitudes of the pendulum. This appears to be because a thicker spring wraps less closely to the cheeks and less correction is applied.

Suspension changes

In carrying out the hill tests we tried Clock B with four different thicknesses of Ni Span suspension spring. The resulting hill tests can be seen in Figure 3, and the
reason for the term ‘hill test’ will be apparent; the ideal adjustment will see the rate increase towards the running arc, then pass over the top of ‘the hill’, placing the running arc just on the other side.

The thinnest spring we fitted was 0.05mm (A). In fact this spring was so thin that the path of the pendulum was quite unstable and it was never going to be a viable suspension, but it was possible to derive a trace for the rate.

We tried a thicker spring of 0.09mm (B), and this resulted in the beginnings of a hill, but the position of the running arc, at 6 set-ups of the remontoire, was still on the ascent of the hill which was not what we needed.

With a spring of 0.11mm (C), which was actually the spring which Martin Burgess supplied with the clock, we begin to see the hill properly forming, but it’s still too far over to the right of the running arc.

It was at this stage that I began to wonder if we would find any spring of a suitable thickness which would fit the bill, and asked Frodshams to source some new Ni Span material somewhat thicker than the thickest already used. In fact the thickness of what they provided was not much greater, at just 0.12mm (D), but by chance, the material, although nominally the same, appeared to have a noticeably
greater Modulus of Elasticity as it was distinctly stiffer, probably owing to heat treatment.

**Success**

This difference in elasticity appears to have provided just what was needed, as when we fitted the new suspension and carried out the hill test, we saw the trace tipped over, and we had the further slope of the hill right on top of the running arc. This provided a gaining tendency as the arc reduced and, in theory at least, would provide at least some correction for changing air density. And so with this suspension spring in place, we screwed the perspex case closed and started to run the clock to see how it responded.

As before, we were immediately struck by the apparent stability of the clock’s rate, but this time we were in for quite a surprise. Soon after the new test had begun we had a considerable fall in the barometer, just as we had had on the previous trial, but this time the clock appeared completely unaffected. After about ten days of seeing no error appear at all, in spite of significant changes in the barometer, I made the decision to have the case bolts independently locked and sealed with impressed wax seals, so that, just in case the clock did perform well, no one could suggest we had tampered with the clock. This official closing was undertaken at the beginning of April 2014 by the National Physical Laboratory, the UK’s national standards organisation, and by the Worshipful Company of Clockmakers.

As described in the earlier article in the Horological Journal, the clock has been running ever since and has, several times over, performed to within a second in 100 days. In fact in April this year, on the two-year anniversary of the official wax-sealing of the case, representatives of both the NPL and the Clockmakers Company returned to Greenwich and confirmed the seals were intact and that the clock was actually reading zero error on GMT (including allowance for the single UTC leap second which had been applied during that period). In all that time the maximum error displayed by the clock was a loss of just over two seconds, during the very hot Summer of 2014, after which the error slowly returned to near zero in the cooler weather. Given the stability of the clock’s running, the question of applying a rate was never even a consideration.

**Temperature Coefficient**

In spite of this exceedingly good performance, it was clear looking at the data that by introducing the barometric (‘air-density’) compensation, the clock was now somewhat under-compensated for temperature (see Figure 4).
It was only because I had carefully regulated the clock to zero for the mean temperature in the room, that (like the barometric effect previously) the changes produced a ‘give and take’ situation, keeping the clock within one second’s error. Before the barometric adjustments, the clock had been correctly temperature compensated in the pendulum, when it was running closer to isochronous, and in introducing a little an-isochronism we had induced a new species of temperature effect, caused by the arc changes.

Evidently, when the air density changes with a change in temperature, the arc does not change as much as the equivalent change in barometric pressure, and without the requisite change in arc, the correction is insufficient. This is happening to the clock, and it is what Harrison *predicted* would happen to the clock, as he states quite clearly that the pendulum should be “shorter when warm” (i.e. slightly over compensated). But *why* the arc does not change as much, is uncertain. It has been suggested that changing air *viscosity*, a separate effect from changing air density, will cause this anomaly, but air viscosity (counter-intuitively) is greater in higher temperatures, the reverse of what would explain this phenomenon. Similarly, if the elasticity of the remontoire spring reduced somewhat in higher temperatures this would affect the arc, but would have the reverse effect of that causing the anomaly, and the question still requires explanation.
We do know that Harrison himself was aware of potential sensitivities to wide temperature change, and was careful to state clearly that his clock should be kept in a “… pretty temperate place”, to minimise any such problems. Notwithstanding this advice, Clock B has been running in the Horology Workshop for over two years, in a very ordinary workplace environment, without any special temperature control beyond radiators used in winter, and a ventilation fan in Summer, to make the space acceptable for human habitation.

Burgess B is now due to be moved into the Harrison Gallery at the Observatory and set running again in October this year for future trials. It remains to be seen how well it suffers the disturbances of millions of visitors passing directly by the case – that will be an interesting challenge for it! Meanwhile, the proceedings of the two Greenwich conferences (Decoding Harrison, in 2014, and Harrison Decoded in 2015) are due to be published in the coming year by the NMM, so the detail of these trials will be available to all.

Commentary

As stated earlier, there have been a number of questions and comments made about the trials of Clock B, and about the implications of its successful performance, which require answer and clarification.

Euphoria?

In spite of the verified and extraordinary performance of Clock B in the last two years, some horologists remain unconvinced and have remarked to me on what they describe as the ‘euphoria’ and the ‘hysteria’ surrounding this work. Personally I am unaware that anyone has been hysterical in their discussions of these trials. Yes, those of us involved in the trials are excited at the clock’s performance, but then I would like to think that any reasonable and impartial horologist ought to be excited by the implications of the results. None of us is seeking congratulation, we were, after all, just working to Harrison’s descriptions and were effectively ‘only obeying orders’. But I think I can speak for others too when I say we are pleased that Martin’s work, and Harrison’s design principle, have been vindicated.

Unfair Advantages?

Some have remarked that the trials have given unfair advantage to Clock B as the temperature range has been very controlled and because the clock has had the advantage of the soundest possible foundation for fixing it.
Perhaps it would be helpful to those who have only taken an interest in this research in more recent years to explain that ever since the Harrison Research Group began looking at Harrison’s designs and claims in the 1970s, the simple basis on which we have considered and compared Harrison’s work has been the existing horological context. If, for example, we claim that the performance of a Harrison clock is ‘better’ than another clock, it goes without saying (I hope) that one compares like with like. We do indeed now believe that over the last two years this clock has out-performed any other mechanical clock with a pendulum swinging in air and, arguably, any in atmospherically controlled tanks too. In making such a comparison it is important to remember that all such equivalents, such as the Shortt clocks at Greenwich and elsewhere, would have been subject to the greatest care to control temperature and any physical disturbance – not something we took anything like the same care about.

Temperature?

Yes we made sure the workshop was habitable and if it was cold we turned on the radiators until it was pleasant enough to work, and if it was too warm to be comfortable in the Summer, we would put on the ventilation fan. But nothing beyond that, and the temperature did indeed vary by considerably more than ten degrees centigrade during the course of the two years. Besides, the creator himself has given specific instructions on avoiding large temperature changes, and it is not unreasonable, nor unfair, to have sought “a pretty temperate place”.

Solid Foundation?

As for having a solid fixing, again Harrison states that the mounting for the clock should be as firm as possible. And which precision pendulum clock intended for accurate timekeeping would not be fixed to a solid foundation? The Shortts at Greenwich were fixed up on the most massive imaginable foundation, onto bedrock, in an underground and closely-temperature controlled cellar. Was that giving them “an unfair advantage”?

Serendipity?

Some have gone as far as to suggest that the extraordinary performance of Clock B has simply been the result of chance. It is said that the environmental factors affecting a pendulum clock are so many and varied, and the permutations so ‘labyrinthine’, that a single system could not possibly account for them, and that ‘serendipity’ has aided the result. These commentators echo the words of the notoriously critical Thomas Earnshaw (1749-1829), who said of other chronometer
makers, that *if their chronometers went well it is only because, unknown to them, one error must be compensating for another!*

If however, this really is their point, then one must ask, are they really suggesting that, day in day out, week in week out, month in month out, over the course of more than two years, this multitude of labyrinthine factors have miraculously managed to each just compensate for another, just at the right time? The probability of such a thing happening is vanishingly small. In fact, an interesting conclusion from the trial is that there would seem to be a limited number of factors significantly affecting a pendulum’s performance and that it is, after all, possible to account for them.

**Limits of materials?**

There is also another inference here which might tentatively be drawn, which is on the question of the constraints imposed on a given precision clock simply by the limits on the stability of the materials with which it is made. More than once I have heard it said that timekeeping better than a second in 100 days is unlikely to be possible with a mechanical clock as the very materials themselves will be insufficiently stable over the longer term. There is nothing particularly special about the materials of which Clock B is constructed yet it has far exceeded the limit of a second in 100 days. Yes, the pendulum rod is of Invar and the suspension and remontoire spring are in NiSpan, but these were not especially treated for this application and the other materials the clock is made of are quite standard, so have we over-estimated this concern in our reckoning?

**Just one clock?**

It has also been observed that even if this clock really is such a stable timekeeper, it is only one, and its creation might itself also be serendipity. This is a reasonable observation, and one can only encourage others to be made soon, to verify these results if possible. However, with such a long period of stability, logic indicates that there is something about this design which is inherently sound and that it is exceedingly unlikely to be a one-off chance construction.

**Complex to construct and adjust?**

Another myth concerning Harrison’s pendulum clock design, mentioned earlier, is that the design would have been impossibly complex and expensive to build and impossibly difficult to set up and adjust. This idea may have originated in the problems which we know Harrison had in *developing* the system, and which
Martin Burgess experienced in his interpretation of Harrison’s principles, in his two clocks, A and B. As William Harrison remarked of their longitude watch: “for it is well known to be much harder to beat out a new road than it is to follow that road when made”. However, now that Martin’s design is finished and tested, we know what to make and we know how to adjust it, which, as described, is not difficult. Yes, the clock has a remontoire which involves extra work in manufacture, but it is a robust design and once made has not proved to be problematic.

Not really Harrison?

In claiming that Harrison’s design has been vindicated by these trials, it is observed, quite reasonably, that Clock B appears very far from the same as Harrison’s late regulator. This is certainly true in part, and I don’t believe any of the Harrison Group concerned in this project would claim that this is absolute proof of how the late (RAS) regulator would have performed. It needs to be made clear, if it hasn’t already, that it is Harrison’s principle of the oscillator system as a whole - so very different from that prescribed by the horological establishment over the last three centuries – which has been researched, and revealed as based on sound thinking.

The problem with Q?

As mentioned, from the very beginnings of the Harrison Research Group (HRG) in the 1970s, the designs of John Harrison were, naturally enough, constantly the subject of comparisons with more conventional horology. Some who were interested in precision pendulum theory, but were inclined more towards the established view, inevitably introduced the question of the quality factor Q. Over the last forty years Q has been a constant presence in discussions over the viability of Harrison’s pendulum technology. Those traditionalists took a kindly interest in the ideas coming out of the HRG, but the politely sceptical message they fed back was clear - the Harrison pendulum is always going to be limited in its capabilities owing to its relatively low Q. It is interesting to note these days, now that Burgess B is performing so well, that those same traditionalists have changed message and are now saying that “Q is quite irrelevant to the discussion of Harrison’s technology”. It is unclear why this should now be the case.

Historical Significance?

The proven performance of Clock B does, to some extent, seem to inform the likely performance of a ‘Late’ (RAS) type regulator. Although we can only be sure
of this once replicas are complete and tested, such a design appears likely to perform considerably better than the kind of regulator available to the scientific world of Harrison’s day, and if eighteenth century astronomers such as Nevil Maskelyne had listened to Harrison and had encouraged him to complete his regulator and made others, eighteenth century science would have had a time standard not seen until the 20th century. But here is where another myth has appeared in recent times. Some commentators now suggest that even if the Harrison design was capable of such a fine performance, the eighteenth century scientific community actually did not need a better time standard and were content with what they had! This is reminiscent of the child who, when told he can’t have something, then remarks that he didn’t want it anyway!

The scientific community certainly wanted better timekeepers - we know that throughout the history of science, practitioners like Maskelyne were always looking for better, more accurate instruments. Specifically in Maskelyne’s example, he and the Board of Longitude on which he sat, were constantly searching for improved designs for pendulum regulators. And they were prepared to spend considerable sums of money to encourage improvements, a practice which continued throughout the nineteenth century with George Airy and into the twentieth century. Every observation on the transit instrument required not only accurate measurement of declination, using the degree scale on the instrument, but Right Ascension - the sidereal time at which the body being observed transited the meridian. The more accurate the regulator, the more accurate the observation, and errors in the regulator translated directly into errors of star position, so accurate timekeeping was vital, especially given variable weather conditions in the UK and the likelihood of many days between checking the clock by observation of clock stars.

**The Theory**

The excellent articles by John Haine and Andrew Millington provide a fascinating mathematical model for how Harrison’s pendulum clock system works, and appear to confirm that his thinking was sound. However, whether Harrison himself applied much in the way of complex mathematics in his work is doubtful. It seems more likely that, for the most part, his philosophy and practical designs were in fact based, to use his own words, “…on Reason and Experience”.

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