The trouble with pendulums

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Much of the collaborative study of John Harrison’s unique pendulum clock system that informs many of the papers in this volume has consisted of decoding the pertinent information contained within a curious publication written by Harrison in 1775. The full title of this work is: *A Description concerning such Mechanism as will afford a nice, or true Mensuration of time; together with some Account of the Attempts for the Discovery of the Longitude by the Moon: as also an Account of the Discovery of the Scale of Music* (Harrison, 1775).

The long-winded title does give the reader a real sense of what follows. This is an extraordinarily difficult read. There is a distinct economy of full-stops, footnotes occasionally span several pages and there are even some footnotes with footnotes of their own. Furthermore, any clues as to how to go about constructing a Harrisonian pendulum clock are unordered and jumbled up among the extra subjects promised by the book’s title. Throughout, the text is interspersed with anecdotal and often vitriolic accounts of his involvement in the longitude story, and in particular, his interactions with the ‘professors (or priests)’. To further compound the ambiguity of the volume, CSM contains no illustrations of the clock nor of its components.

There is a deeper problem with the language of horology. There are a limited number of early treatises from which a reasonable glossary of terminology can be assembled. However, the practice of training and transfer of knowledge followed an oral tradition from master to apprentice and so numerous vocabularies have developed according to each master’s lineage. Harrison, having arrived in the arena without formal training, had a vocabulary based on the texts that he had read and, in connection to his own work, developed new terminologies that were not readily translatable. For example, Harrison uses the word ‘dominion’ to describe the dynamic relationship between the pendulum and the escapement. This single word encompasses a concept that is described later on in Chapter 8. This type of communication problem is comparable, perhaps, to words such as the Danish word *Hygge*, which conveys a feeling of contentment that is bound to a unique cultural paradigm, and therefore cannot be translated to a single word from the English language.

A contemporary review of CSM opens thus:

> *The curiosity of the Public may perhaps be raised in expectation of having the principles of Mr Harrison’s celebrated time-keeper fully explained, the many curious contrivances in his machine clearly described, and their uses pointed out by the inventor*

> *himself. We are sorry to say the Public will be disappointed (Anon, 1776:330).*

It is hoped that this volume will redress the balance and lay bare the intricacies of Harrison's pendulum clock system. This chapter will provide the reader with an overview of the mainstream development of the precision pendulum clock, which is intended to provide some historical context to Harrison's work and complement the other chapters in this volume by explaining some of the key physical problems that affect mechanical pendulum clocks.

The pendulum as a time-measuring device

The pendulum's history as a timekeeping device begins around 1600. Galileo Galilei, as perpetuated by his student and first biographer, famously observed the isochronous properties of a swinging lamp in Pisa cathedral. Using his pulse as a time standard he concluded that the larger arcs of swing took the same time to complete their action as the shorter ones. Galileo went on to use the pendulum as a time standard in his experiments, intending to derive a constant for natural acceleration. However, the pendulum alone was not an appropriate instrument with which to time the descent of rolling balls down an inclined plane, for example. There was too much room for error in observing the pendulum by eye in conjunction with a fast-moving sphere.

The pendulum served to calibrate a simple form of water clock, known as an outflow clepsydra. This device consisted of a large water-filled vessel with a small opening at the bottom that allowed a constant stream of water to escape. Galileo collected water from the clepsydra in a glass. The amount of water collected was metered by the oscillations of the pendulum. In this manner, Galileo was able to provide an arbitrary time measurement in terms of the weight of water collected. This method provided relative values for distance travelled over a given period. In *Dialogo,* he presents his results for acceleration in this manner - distance over weight of water collected (Crew and Salvio, 1914:179).

The pendulum, in its simplest form, is a weight (the bob) suspended from a fixed point, which when set in motion swings from side to side. A left-to-right motion of the bob is called a vibration and a full cycle, say, left-to-right and back again, is known as an oscillation. By experimenting with bobs made from both lead and cork, Galileo was able to conclude that the weight or density of the pendulum bob did not affect its period, though air resistance reduced the cork bob's arc of swing much faster than its lead counterpart. Further experiments demonstrated that it was the length of the suspension that dictated the duration (period) of a vibration. He also found that the relationship between length and period was not linear but was governed by a square law. For example, to double the period of a pendulum, the length of the needs to be multiplied by four.

Presenting time in terms of weight of water collected was not ideal. Galileo, assisted by four ‘patient and curious friends,’ attempted to quantify the period of the pendulum. The arduous process of maintaining and counting the vibrations of a simple pendulum was described in a letter to his friend and long-term correspondent, Giovani Battista Balliani (1582–1666). Between successive transits of a bright star, the team counted a total of 234,567 vibrations during the 24-hour period, which suggests that their pendulum had a period of around one-third of a second. However, the consecutive nature of the digits in his total number of vibrations and the fact that he continued to use weight rather than seconds of time in *Dialogo*, published after the experiment, suggests that he was not confident in the result (Drake, 1978:399).

Other philosophers, such as Marin Mersenne (1588–1648) and Giambattista Riccioli (1598–1671), also attempted to identify the length of a pendulum with a one-second vibration in a similar fashion. Again, the 24-hour manual process proved too laborious and attempts to shorten the time taken to calibrate the pendulum by use of other instruments, such as clocks, sand glasses and sundials, were unsatisfactory due to their imprecision. An automated system that could automatically maintain and count the pendulum’s vibrations was required – i.e., a mechanical pendulum clock. The first published description of such a device came from the brilliant Dutch mathematician and astronomer Christiaan Huygens (1629–1695) in the 1658 pamphlet *Horologium* (Edwardes, 1970:35).

Circular deviation

By this time, it was understood that the pendulum was not isochronous, as Galileo had assumed. If a pendulum follows a circular arc it will inevitably take longer to swing over a large arc than a short one. This characteristic is commonly known as circular deviation. The French theologian and philosopher Mersenne was aware of this but, like Galileo, he did not factor it into his pendulum experiments. Huygens identified that a pendulum swinging along a cycloidal path would have the same period, regardless of its amplitude. The cycloidal curve is drawn by a single point on the circumference of a circle that rolls along a straight line. Importantly in pendulums, the cycloidal path means that the pendulum’s effective length shortens as the arc increases, and so with the correct curve the pendulum becomes isochronous.

In the fourth section of *Horologium Oscillatorium* (1673), Huygens credits Mersenne for introducing him to the cycloid. The two men never met but corresponded after an introduction by Christiaan’s father, Constantijn Huygens (1596–1687). Huygens created a desirable path for the pendulum by means of a pair of metal curved cheeks that enclosed the pendulum’s silk suspension and, in theory, they rendered the pendulum isochronous by shortening its effective length as the arcs of swing widened. With this device, Huygens’s mechanical pendulum clock was substantially better than its best-performing predecessors, bringing the daily instability down from around one minute to around ten seconds (Yoder, 2004:12).

Unpredictable changes in the pendulum’s arc of swing are unavoidable in a mechanical clock of this early type. The following factors are listed roughly in order of their effect on such a clock’s timekeeping: variations in the energy transferred to the pendulum by the escapement, caused by mechanical imperfections in the clock movement; the changing properties or location of the oil lubricating the clock’s moving parts; and changes in barometric pressure, and particularly temperature. It is important to note also that the effect of circular deviation is not linear. The relative change in period increases in the larger arcs of swing. For this reason, clockmakers attempted to minimise the pendulum’s arc of swing to diminish the effect of circular error.

Towards a perfect oscillator

In scientific terms, clock pendulums are oscillators. Depending on the way a pendulum is used or maintained, it can be categorized in different ways. For example, Huygens’s cycloidal cheeks is close in principle to being a linear oscillator – where the speed of the return of the pendulum increases with an increase in amplitude (or vice versa) and thereby maintains a constant period. However, in practice the mechanical movements that drove the pendulums had too much of an influence over the pendulum’s motion for the system to be effective or come close this theoretical ideal.

The Curator of Experiments at the Royal Society in London, Robert Hooke (1635–1703), experimented with pendulum clock design, pursuing a different arrangement, where a heavy pendulum bob received a small impulse and minimised circular deviation by swinging over a very small arc. In 1669, Hooke demonstrated his design to the Royal Society, using a 3lb lead ball suspended on a string of around 14 feet in length and an adapted a pocket-watch movement to keep the pendulum swinging, making one vibration in two seconds. In theoretical terms, Hooke’s pendulum was a simple harmonic oscillator and arguably set the template for the precision pendulum clocks through to the late nineteenth century.

The subsequent discussions that ensued at the Royal Society following Hooke’s demonstration of the design are scantly reported, but are fundamental not only to the history of the precision pendulum clock but also the history of the Royal Observatory, Greenwich. Hooke’s remarks on the design are reported in the journals of the Royal Society and, on 26 June 1669, he made these two important statements regarding his design: 'the smallness of the vibrations renders the pendulum insensible of the impression, which the watch makes upon it, said, that the weight appendant to the string was so great, that the impression could have no power upon it' (Birch, 1756:388). Firstly, the impulse given by the watch was so small in proportion to the energy stored in the swinging bob that it could maintain but have almost no effect on the amplitude or period. Secondly, the low-energy impulse from the pocket watch movement was delivered to the bob and, therefore, was unable to distort the pendulum's shape by curving the string. The ill-effects of energy loss through distortion of the pendulum's shape evidently concerned clockmakers. Some years later, William Derham (1657–1735), author of one of the first clockmaking treatises in the English language, described how one of his clock pendulums was constructed specifically to resist deformation: 'the pendulum rod flat & strong, broad at the bottom, & tapering all the way to the top. But without such a provision, the rod by bending … makes considerable alterations in the length of the vibrations' (Derham, 1714).

In 1675 the Royal Observatory was founded and John Flamsteed (1646–1719), the first Astronomer Royal, was provided with two exceptional pendulum clocks that were integral to the structure of the room, known today as the Octagon Room. These two clocks were made by the famous clock and watch-maker Thomas Tompion (1639–1713) and were designed to run for one year between windings. Each had a two-second pendulum suspended above its movement and, as in Hooke's 1669 demonstration, they maintained their pendulum's swing from below, with a very light touch. When the Observatory's architect Christopher Wren (1632–1723) saw Hooke's timekeeper in 1669 he suggested that it could be improved by use of a 'cylindrical staff of 28 feet long, and making it move in the middle on a pin, and hanging an equal weight on each end of it, to be moved with a pocket watch.' Had this idea been implemented at Greenwich, the shape of the Octagon Room would have necessarily been vastly different to accommodate such a clock (Birch, 1756:361).

The clocks were indeed far superior to anything else of the time in terms of their timekeeping; however, they were very problematic and stopped regularly, requiring cleaning and re-oiling, across the early years of their use (Howse, 1970:27). Despite the frequent stoppages, the clocks enabled Flamsteed to determine that the Earth's speed of rotation was constant throughout the year. Previously, this was assumed and Flamsteed's assertion became a solid foundation for the positional astronomy at Greenwich that followed. However, in the late nineteenth century, inconsistency between predicted and observed positions of the Moon revealed to astronomers that the speed of the Earth's rotation showed some seasonal fluctuation. This seasonal disparity was far smaller than the daily instability of Flamsteed’s clocks at Greenwich. Flamsteed’s records of the clocks’ performance in 1677 show that they could be relied on to keep time to within around six seconds per day [fig.1].

Fig.1 Average daily rate of a Tompion year-going clock (with ‘pivoted pendulum’) at Greenwich from March 16, to May 19, 1677.

Please label vertical axis ‘Rate seconds/day’ and Horizontal axis ‘Days’

The dead-beat escapement

Flamsteed corresponded regularly with Richard Towneley (1629–1707), a friend of Flamsteed’s patron Sir Jonas Moore (1617–79), keeping him up-to-date on developments in London. From surviving letters we have learned that Towneley was likely to have been the first to make a form of the dead-beat escapement and that Thomas Tompion (1636-1713) made a clock for Moore with a similar escapement soon after. Flamsteed wrote to Towneley in September, 1675: ‘I hear not of any pallets for pendulums that have been made your way, but Mr Tompion likes it very well since as the other it puts not the second finger back by girds.’

The term ‘gird’ refers to the action of the second hand when attached to a recoiling escape wheel, which is never stationary: as it advances one division (two seconds on Flamsteed’s clocks), it moves backward (recoils) before advancing to the next (Howse, 1970:18-34). It is interesting to speculate as to what exactly appealed to Tompion; perhaps it was the precise motion of a dead-beating second hand that enabled a clear reading to the nearest second, or maybe it was a mechanical advantage that encouraged isochronism in the pendulum.

Flamsteed wrote to Towneley, while observing from the Queen’s House at Greenwich, and described the poor performance of his pendulum clock. He explained that the movement had become clogged with dirt and that the low energy imparted to the pendulum had caused the clock’s timekeeping to shift from a loss of 30 seconds per day to a gain of one minute per day. Flamsteed informed Towneley that the escapement was of the ‘old form’, which was likely to have been an anchor escapement with a recoiling action (Howse, 1970:23). The reported change in timekeeping suggests that initially, the losing rate was caused by the distinctive properties of the anchor escapement. Such an escapement will cause a slowing of the rate if the power is reduced. This dramatic increase in clock rate was likely caused by some mechanical failure, as it simply too large a shift to be caused circular deviation alone. In the same letter, Flamsteed intimated that Moore was of the opinion that the dead-beat escapement might have helped to isochronise the clock.

Escapement error

This term is commonly used to describe the characteristics of a particular escapement. The term is a little misleading as 'error' implies a negative quality. In the simplest of terms, this describes the effect caused by the presence of the escapement on the period of the oscillator and the resultant alteration to clock rate at different pendulum amplitudes. The English mathematician and surveyor Charles Hutton (1737–1823) chronicled that George Graham (*c*.1673–1751) and Edmond Halley (1656–1742) conducted a series of experiments at the Royal Observatory and they had concluded that it was the recoiling action of the escapement that caused the acceleration in rate as the arc of the pendulum's swing increased. Hutton also identified Graham as the inventor of the dead-beat escapement. In doing so, he stated that Graham 'restored to the pendulum wholly in theory, and nearly in practice, all its natural properties in it is detached state' (Hutton, 1795:419).

However, in practice the dead-beat escapement has its own unique characteristics, and variations in the pendulum's amplitude also cause changes in rate. Experience shows that the presence of the dead-beat escapement slows the rate of the clock and does so increasingly as the driving force increases. Hutton's piece bolstered the misunderstanding that Graham was the inventor, and indeed the fact that the dead-beat was a superior design. If one analyses the output from Graham's business over its 38-year lifespan, and considers the strict maintenance of a house-style, established by Tompion, it is difficult to maintain the assertion that the dead-beat escapement is the superior design. During Graham's tenure of the business, around 2,500 timepiece pocket watches were produced (based on serial numbering of extant watches). In the mid-1720s, Graham abandoned the use of the verge in favour of the cylinder escapement in his watches. From the subsequent production of around 1,500 watches, only one surviving example features the verge escapement (number 5999). This precedent raises an important question – why weren't all of Graham's pendulum clocks fitted with the superior dead-beat escapement? Graham's longcase clocks feature both forms of escapement and there is no evidence to suggest a preference.

Another eighteenth-century exponent of the dead-beat escapement was Alexander Cumming (1733–1814), who wrote:

> That the influence of the oil and friction, is always less on the dead-beat, than on the recoil; all other circumstances being alike … the recoil can have no tendency to keep the vibrations

> of more equal length. Therefore, that in all cases whatsoever, the DEAD-BEAT is preferable to the RECOIL (Cumming, 1766).

The Reverend William Ludlam (1716–88) was not as dogmatic on the subject of clock escapements and gave a more open-minded view of contemporary attempts to improve clockwork, including good analysis of the work of John Harrison (1693–1775) and other recoiling escapements. Ludlam's occasional references to Cumming's publication are somewhat scathing. He suggested that Cumming had 'grossly misunderstood' some of Harrison's ideas and that his suggestion of suspending the pendulum from a substantial block of marble set into the wall was the best piece of advice in the whole book. Ludlam (1769:138) concluded:

> *How far these inventions may improve clocks remains to be tried. In the mean time, if the pendulum be properly suspended, and its length not subject to be changed by the weather; a clock of the common construction with dead seconds will go well enough for any astronomical purposes whatever … the observatory clock could always be depended upon for ten days or a fortnight, so as not to gain or lose in that time above a second or two at the most, an astronomer must have bad luck indeed, if in that time he cannot take a [sic] observation either of the Sun or stars by which he may examine the going of his clock, and determine its error.*

Weather and the pendulum

Ludlam's description of the typical astronomical clock mentions the importance of having compensation for 'weather' on the pendulum. To fully understand the Harrison system, it is essential to have a working knowledge of how changes in environmental conditions affect pendulum clocks. Harrison deliberately made his pendulum more susceptible to changing conditions of the air to enable compensation – unlike the majority of precision clock-makers who opted to avoid or, at best, minimise the effects of changing conditions.

From the early days of the pendulum clock, natural philosophers were keen to interrogate the physical properties of the pendulum and the vacuum pump was a valuable tool in such endeavours. Robert Boyle (1627–91) conducted early experiments with free-swinging pendulums inside an evacuated chamber. Boyle's goal was to study the effects of air pressure on the decay in amplitude of an undriven a pendulum and, from his experiments, determined that there was 'no sensible difference between the celerity of a pendulum's motion in the air and that *in vacuo* [sic]' (Birch, 1756:429).

In 1704, William Derham (1657–1735) also studied the pendulum in an evacuated chamber. Unlike Boyle, he placed a pendulum clock in the receiver to study the effects of air pressure on timekeeping. He observed that the pendulum’s arc of swing increased as the air was evacuated and that the clock slowed by two seconds per hour when the vibrations were at their largest. This was an anticipated product of circular deviation. However, Derham suspected that the pendulum was moving faster in the vacuum and through ‘nice experiments’ was able to confirm his suspicion. He demonstrated this by running the clock in air and adding to the driving weight until the same enlarged amplitude was reached. The clock ran almost three times slower than it had in the vacuum.

Derham’s experiments very neatly illustrate the following effects of changing air density on ordinary pendulum clocks. A reduction in air density will reduce air resistance and thereby increase the amplitude of the pendulum. Circular deviation will cause the period to increase; however, the thinner air offers less buoyancy to the pendulum, and so the gravitational pull on it is greater, which causes the bob to travel at a greater velocity and reduces the effect of circular deviation. Derham’s latter experiment showed that an increase in air density will have the opposite effect (Derham, 1735).

The shifting levels of gravity and air resistance acting on the pendulum can be caused by both barometric pressure and temperature. However, these two causes do not have the same effect. On the one hand, a change in barometric pressure alone will affect a pendulum clock in the same manner as described in Derham’s experiments with the evacuated receiver. On the other hand, colder temperatures will increase air density but the secondary effect of drag, the air’s viscosity, differs. Despite the increased density, the colder air is more inert and so the pendulum bob experiences less drag. Temperature also has a greater influence on clock rate, as the materials that make up the clock movement – particularly the pendulum – expand and contract in changes of temperature.

Whilst George Graham never claimed priority of invention for the dead-beat or cylinder escapements, he did invent the first temperature-compensated pendulum (Graham, 1722). Because the period of a pendulum is governed by its length and because most pendulums were made from brass, steel and lead, when the temperature rises, the pendulum’s components expand and thereby slow the clock’s rate. By replacing the pendulum bob with a mercury-filled glass jar, Graham’s pendulum maintains a constant centre of gravity in changing temperatures. The upward expansion of the mercury in the jar compensated for the elongation of the metal rod. The consequence of changing air density due to temperature variation is often unconsciously compensated for by the clockmaker. In a mercurial pendulum, the compensation is achieved by fine-tuning the amount of mercury in the jar.

To improve or not to improve

In 1749, a clock with all of the refinements mentioned above was purchased for use at the Royal Observatory by the third Astronomer Royal, James Bradley (1693–1762). The clock, known today as Graham No. 3, was the epitome of an excellent astronomical clock with dead-beat escapement and temperature-compensated pendulum (Harrison's grid-iron) – the type that Ludlam advocates 'will go well enough for any astronomical purposes whatever.' The integrity of Ludlam's statement is upheld by the fact that the format of the majority of such clocks remained mostly unchanged throughout the history of mechanical clock production. However, Graham No. 3 contains rich archaeology that illustrates repeated attempts to improve its performance. Its history bears testament to the fact that Nevil Maskelyne (1732–1811) did not consider the design to be adequate and throughout his tenure at Greenwich continually sought a better time standard for the Observatory.

The success of Harrison's fourth timekeeper opened up a new facet to the role of Astronomer Royal. Maskelyne, being the country's foremost expert in time derivation, was charged with testing the nascent marine timekeeping technology. The first trial at Greenwich was that of Harrison's fourth timekeeper, known today as H4, and the daily record of the watch's timekeeping was published alongside the error of Graham No. 3, temperature and barometer readings.

Astronomers at the Royal Observatory determined the daily error of the clock by observation of the transits of bright stars across what is known today as Bradley's meridian. These stars were often referred to as clock stars for they were used to indicate the local sidereal time. To make an observation, they read the time to the nearest second from the clock before turning their eye to the telescope. Then, continuing to count the audible ticking of the clock, they observed the relative positions of the star, for two successive ticks, either side of the vertical wires that segmented the field of view from the telescope. They used a graticule in the eyepiece to gather a series of timings from which an average could be made to obtain the most precise value for the clock's error at the time of the transit.

The published record of the trial is an extraordinary document that encapsulates the day-to-day performance of one of the country's best clocks in the mid-eighteenth century (Maskelyne, 1767). Figure 2 is drawn using Maskelyne's published results and follows his method of presentation. Positive values indicate that sidereal time was ahead of the clock, therefore that the clock was losing, and vice versa. Additionally, the average daily temperature and air pressure was recorded; these values are represented on the chart above and below the clock rate for ease of reading. From this data one can infer that the clock was, on the whole, a reliable timekeeper that kept time to around a tenth of a second for most days, albeit with a gaining or losing rate. However there are numerous examples where the clock’s error changed by as much as half a second in one day. Three months into the trial of H4, Maskelyne’s assistant, Joseph Dymond, stopped the clock and adjusted the pendulum length to correct its gaining rate. This event caused the sudden shift in the graph, seen one-third of the way along (Maskelyne, 1767:xii).

Fig. 2. The going of Graham No. 3 during the trial of H4 at the Royal Observatory between May 6, 1766 and March, 4 1767.

The data indicates an occasional correlation between clock rate and changes in barometric pressure, though not with great regularity. There are some highs and lows in barometric pressure that do not appear to have any discernible effect on the clock’s rate. Additionally, there are shifts in the rate that appear unrelated to changes in environmental conditions and which are likely to have been the result of shifting states of lubrication within the clock movement. Dymond’s intervention in early August follows Ludlam’s summary of the use of pendulum clocks in the Observatory – they were somewhat wayward servants and required regular correction according to the astronomers’ observations.

In October 1794, Maskelyne’s assistant David Kinnebrooke Jnr described to his father the instruments that he used at Greenwich, and in his (1794) letter he remarked that Harrison, Arnold, Kendall and Earnshaw had all had a hand in improving Graham No. 3. Beyond Kinnebrooke’s letter, surviving records do not confirm Harrison’s involvement with Graham No. 3. It is possible that he was confusing some of the upgrades to the clock, such as incorporation of Harrison’s design for maintaining power and the mounting of the pendulum directly to the stone pier, as the work of Harrison. Evidently, Harrison had lost all interest in helping the Astronomer Royal to improve his instrumentation and did not offer a pendulum clock of his design to Greenwich. In his final written work he acerbically remarked, ‘I once thought of giving a clock to the Observatory at Greenwich, but my bad usage proved too tedious for that’ (Harrison, J. 1775:52).

In the years following the Observatory trial of H4, Graham No. 3 was subjected to a series of improvements, made by the precision watchmakers on Kinnebrooke’s list. It is not a coincidence that the timing of these interventions coincided with the deliveries of new marine timekeepers for testing at the Observatory (McEvoy, R. 2014). Maskelyne’s observations fed into calculations that provided the predicted relative positions of the planets, stars and the moon in the Nautical Almanac. Inaccuracy could result in loss of life at sea and so it is unsurprising that Maskelyne actively sought to improve his instrumentation. Indeed, in the late nineteenth century, thanks to improved observation equipment, astronomers noticed a regular disparity between observed and predicted positions of the moon. This disparity was later identified as a product of seasonal fluctuations in the Earth’s speed of rotation.

In 1807 Maskelyne took delivery of a new design of transit clock from William Hardy (d.1832) for trial at the Observatory. Maskelyne records the clock as having a detached escapement, suggesting that the pendulum was free of unwanted frictional influences. In fact, the clock had a spring pallet escapement, which can more correctly categorized as a constant force escapement. The trial showed that the design offered far greater accuracy than Graham No. 3. Maskelyne’s (1807) manuscript record has been represented graphically using a scatter plot [fig. 3]. This type of chart effectively illustrates the clock’s margins for error. From day 20 on, the clock consistently indicated time to within half a second. However, the design was not without its problems. During the first 20 days, the clock’s performance was erratic because of a fundamental flaw in the design. During this period, the lubrication of the escapement had failed due to ingress of dirt. The clock’s stability was absolutely dependant on the condition of the escapement’s lubrication. Maskelyne noted that on days 17 and 18, the clock pallets were cleaned and re-oiled.

Fig. 3. The going of William Hardy’s clock at the Royal Observatory from June 29, to July 13, 1807.

Please label vertical axis ‘Rate seconds/day’ and Horizontal axis ‘Days’

The good performance of Hardy’s clock was partly due to the fine and careful construction of the wheelwork. Due to the escapement’s dependency on a perfect state of lubrication, the new transit clock was converted to dead-beat escapement by the ambitious EJ Dent (1790–1893), not long after its installation at Greenwich [Plate 1].

The nineteenth century saw continued development in pendulum clock-making, and some notable examples were of a sufficient quality to be predictably affected by changes in barometric pressure. Dent no. 1906, for example, served as the Sidereal Standard at Greenwich for over 40 years. When first installed in the magnetic basement in 1871, its timekeeping was so stable that it responded predictably to changes in air pressure; a rise of one inch of mercury caused the clock to lose 0.3 seconds per day (Airy, 1872:xxiv) Today, this clock has a glazed door, fitted for display at the Festival of Britain in 1951, to show off the barometric compensation. A mercury-filled J-tube (typical of the type found in wheel barometers) and a see-saw type arrangement with a float at one end and a horseshoe magnet at the other corrected the period of the pendulum, compensating for changing air density by more or less interaction with two bar magnets strapped to the pendulum bob.

Thomas Romney Robinson (1792–1882), the astronomer at Armagh Observatory, had previously attempted to compensate for changes in air density by attaching a barometer tube to the clock pendulum. In his 1843 paper, he mentioned Edward Sabine’s (1788–1883) pendulum experiments that had been conducted inside an evacuated chamber and expressed a wish that a transit clock could be made to run inside an evacuated chamber (Robinson, T.R.1843:18). Edmund Beckett Denison (1816–1905) advocated the use of a large arc of swing in larger clocks to use circular deviation to correct for the effects of changing air density (Beckett, 1903:74). This fine balancing act is challenging enough, but with frictional escapements, at the large amplitude required, they may produce greater errors than the air density issue that was being corrected for (Robertson, 1929:196).

Towards the end of the nineteenth century, Robinson’s wish for a clock that could be run reliably in a tank of constant pressure became a reality. The first commercial clocks were produced by Sigmund Riefler. His clocks were electrically re-wound every 30 seconds and featured a form of dead-beating escapement that was connected directly to the pendulum through the suspension. According to the company’s marketing material, the clock did offer tremendous stability as a timekeeper of around one hundredth of a second per day. In the early 1920s, a railway engineer, William Hamilton Shortt, devised a way to maintain a pendulum in an evacuated chamber without it being directly connected to an escapement, thus alleviating the clock from the associated problems of escapement error and inconsistency.

Shortt’s free pendulum came close to meeting the desired conditions of a stable harmonic oscillator [Plate 2]. The pendulum bob had a high stored energy, relative to the loss incurred during oscillation, and only required a minimal impulse every 30 seconds to maintain an almost constant arc of swing. Physicists describe this pendulum as having a high Quality (Q) factor. The Shortt system used Invar, an iron and nickel alloy with a very low coefficient of thermal expansion, for the pendulum rod and so it should have been free from temperature error. However, staff at the Royal Observatory found that the clocks did respond to changes in temperature, and also that the amplitude of the pendulums varied, albeit slightly (Jackson and Bowyer, 1928:480).

Staff at Greenwich observed temperature change and the pendulum’s amplitude (in millimetres) to make mathematical corrections to the rate. To minimise the effect of circular deviation, Shortt Free Pendulums operated at a running arc of just under two degrees. However, even with this low arc of swing, the effect of a miniscule change in amplitude was quantifiable. A change of just one hundredth of a millimetre to the semi-arc would amount to an error of a half second after one year (Hope-Jones, 1930:157). Once the clock rate had been smoothed, there were still inconsistencies evident in the timekeeping.

Changes in gravity, caused by the Sun and Moon, affected the timekeeping. This effect was likewise mathematically corrected. Invar showed some material instability and this was identified by the varying performance between Shortt clocks. In addition to these, there was one unpredictable influence: seismic activity. It is arguable that this influence is one of the worst enemies of stability in high Q pendulum systems. An extreme example of seismic interference was captured at the Lick Observatory, California by a photographic arc recorder that monitored their Shortt Free Pendulum. The quake caused a large increase in amplitude, and therefore a slowing of the clock's rate. Because of the pendulum's high Q factor, it took over 24 hours for the amplitude to return to the running arc (Jeffers, 1935:79).

The fact that noise vibrations affect clock pendulums, and in an urban environment they come from a multitude of unpredictable sources, is nothing new to clockmakers. In the mid-1730s James Bradley (1693–1762) described how a pendulum clock, used in a gravity experiment, was deliberately set up 'in a room, situated backward from the street, and on the north side of his [George Graham's] house, to prevent its being disturbed by coaches, or other carriages that passed through the streets' (Bradley, 1734). To demonstrate this issue in a modern context, a short film of the pendulum of the Museum's Fedchenko tank regulator was shown at the first conference on Clock B at the National Maritime Museum in June 2014. The clock, displayed in the Time and Greenwich gallery at the Royal Observatory, had no electrical supply at the time and yet the pendulum was oscillating with amplitude that was certainly visible to the naked eye.

This history has remained within the walls of the Royal Observatory, Greenwich and for this reason will draw to a close at the Shortt Free Pendulum Clock. Its mechanical DNA descended from Hooke's design and the first clocks supplied to John Flamsteed at the Observatory's foundation: a large and heavy oscillating weight with light impulse that maintained its swing over a small arc. The Shortt system approached perfection but only with the assistance of mathematical smoothing of its time indication. It achieved a level of precision that revealed the minutest of problems and yet, by virtue of the fact that it required anchoring to the Earth, it was always going to be influenced by noise vibration.

So, perhaps 250 years too late, Martin Burgess's Clock B may have demonstrated that Harrison was on to something remarkable and that there was another way to make an accurate pendulum clock. The ensuing chapters will chart this extraordinary history, reveal the dichotomy between the Hooke and Harrison method, report on the modern-day practical investigation, and present the perceived theoretical approach that almost died with its architect.

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