Pendulum Sensor for the Robertson Clock

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1. Introduction

Previous HSN articles by Bob Holmstrom and myself have given details of the Robertson Clock at Bristol University in the UK. Bob gave a general description whilst I focused on the operation of the automatic regulator and its performance. This short article discusses the escapement in more detail as background for a proposed modification to improve the clock's long-term reliability.

The gravity escapement, activated by an electromagnet, relies on platinum contacts to sense pendulum position. The actual arrangement on the clock is not as originally designed, the mechanical arrangement is not ideal, and occasionally the contacts get out of alignment and the clock stops. Adjustment is difficult and access awkward; and a considerable amount of dismantling would be needed to replace the contacts. As an electrical engineer at the forefront of his profession, if Robertson was working today he would probably adopt a more reliable way to sense the pendulum (assuming that he was designing a mechanical clock at all!). As we have already provided the clock with a processor to replace the function of the seconds counter and drive the dial, such a change is worthwhile to improve reliability even though not in the true spirit of conservation.

2. Escapement principle

Figure 1 shows the escapement diagrammatically.

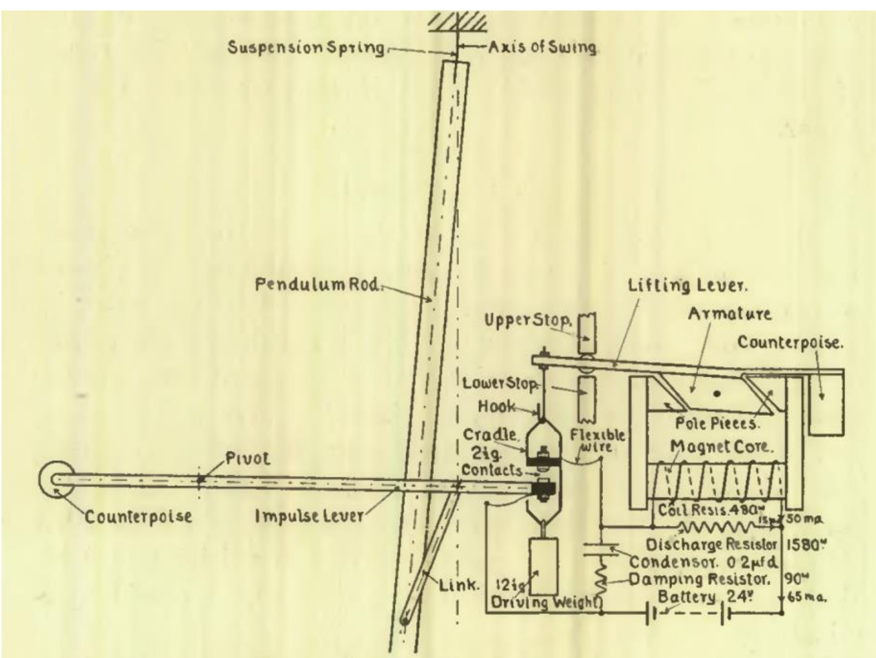


Figure 1: Robertson's escapement diagram

The key components are the Cradle, Driving Weight, and Contacts. Essentially as the pendulum swings from left to right, the Link lifts the Impulse Lever and the contact at its end, and at some point the Cradle and Impulse Lever Contacts complete a circuit that energises the electromagnet. The magnet then moves the Lifting Lever, with a Hook on which the cradle hangs, down between the Upper and Lower Stops (actually formed by the anvils of two micrometer heads which allows precise adjustment), placing the Driving Weight on to the end of the Impulse Lever via the Contacts. The weight is conveyed to the pendulum rod via the Link, and the force has a horizontal component which initially acts against the gravitational restoring force and absorbs some energy from the pendulum. When the rod is vertical the horizontal component is zero; once it passes the vertical the force acts to push the rod away giving energy back to the pendulum. As the Impulse Lever now moves down, eventually the Cradle engages with the Hook again, the weight is removed from the Impulse Lever, the circuit breaks, and the Cradle is lifted up to its starting position by the Counterpoise on the Armature. Since the weight drops through a slightly larger distance than it lifts, a net energy is added to the pendulum to compensate for energy lost to friction etc. Robertson recommends a lift of 0.2mm and drop of 0.4mm, and with a weight of 15g the energy contributed per swing is (0.0002m)x(0.015kg)x(9.81m/s/s) = (2.94e-5)Joules, to give a steady-state amplitude of 3°. The bob weight (not given by Robertson) must be in the region of 7kg assuming it is made of a lead alloy, and the usual expression gives an effective Q of ~10,000. Robertson's reported measurements imply that the dominant loss mechanism is proportional to the square of velocity.

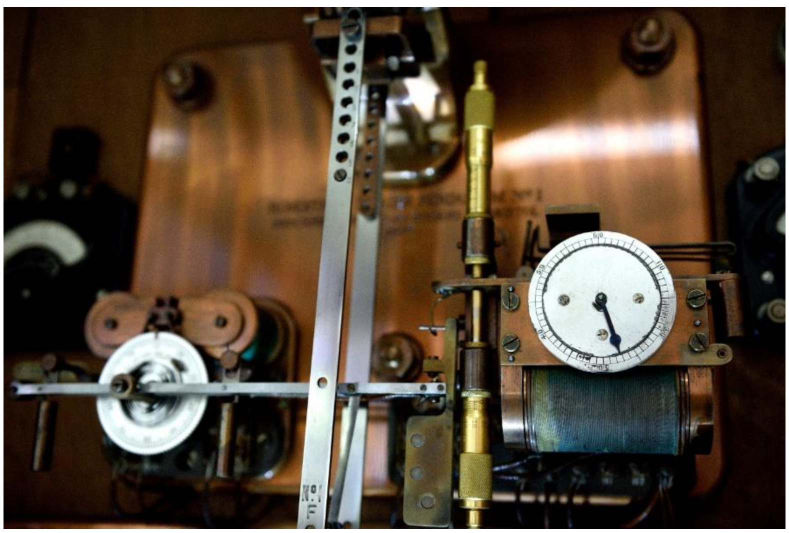
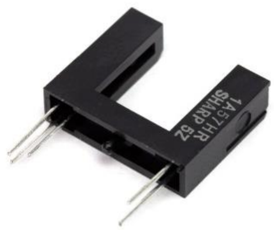


Figure 2: Photo of escapement mechanism

Figure 2 shows the actual escapement and it can be seen that the impulse weight and cradle have been replaced by an oddly shaped ebonite block with embedded weights. We don't know if this was done originally or is a later replacement. The upper contact is connected to the circuit via a thin gold strip projecting backwards and soldered to a thick rigid wire. As a result of the departure from the original design the contacts cannot be perfectly aligned and in fact occasionally fail to make correctly, causing the clock to stop. In any case a pair of platinum contacts has a finite life and will be increasingly difficult to replace.

3. Alternative sensing methods

There are two obvious candidates: an "optical interrupter" using a photodiode and transistor; or a Hall Effect device (HED). Both could sense the pendulum position as it passes BDC using an appropriate projection – a "finial" – on the base of the bob. For the opto this can simply be a short rod to cut the beam; for the HED it needs a small magnet attached to the end.



This photo shows a typical opto device. It has a 10mm gap through which the finial would need to swing. Brief consideration suggested that this could be a problem as, especially when unskilled operatives start the pendulum, it has a tendency to swing slightly at right angles to the desired direction and could easily hit one of the jaws – as the bob weighs ~7kg this would probably destroy the sensor. On the other hand an opto device can be very precise.

An HED is generally less precise because by its nature a magnetic field extends more in space, but on the other hand the sensor could be mounted below the bob with the finial swinging above it, which would be much less prone to collisions. The problem is whether it can be sufficiently precise not to affect the clock's operation?

This photo shows a HED (small black rectangle) mounted on a breakout PCB bolted to a composite pillar. This is held onto the steel mounting plate by a strong magnet embedded in a steel base to minimise stray fields. The mounting plate can be screwed to the base of the clock case, holding the sensor in a position just below the finial, and the sensor pillar can be adjusted by sliding it on the base. Measurements using a coordinate table to move the sensor below a 3 x 2mm neodymium magnet held 5mm above the sensor level show that the HED switches "on" with ~1.2 mm lateral displacement from the centre line and "off" with about 4mm.

4. Timings

The pendulum rod pivots at A and carries the bob mass M at its end. Its length is L. The impulse lever is pivoted at its left end and carries another pivot at B. For the purposes of this discuss its length is irrelevant, only its ratio, which is 4/3. For small angles of swing we can assume that B moves along the centre line axis through the rod pivot point. BC is the link, which is pivoted on the rod at C. The rod and link make instantaneous angles θ and ϕ respectively from the vertical. Point C is distance a below the pendulum pivot, and the link length is b. At a given instant C is distance x from the vertical axis and y below B.

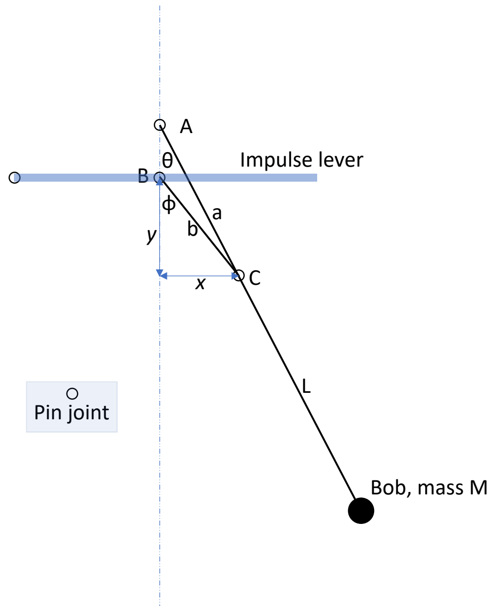


Figure 3: Escapement geometry

It is obvious that:

$$x = a \sin\theta$$

and therefore:

$$y = \sqrt{b^2 - a^2 \sin^2\theta}$$

Figure 4 plots the difference between the position of B at BDC and position at angle θ, which is the "drop". Excel "Solver" gives the pendulum deflection angles for drop of 0.2mm and 0.4mm as 0.98° and 1.38° respectively. Assuming an overall pendulum length to the end of the finial, these correspond to horizontal deflections of the bob of 19.2mm and 27.1mm.

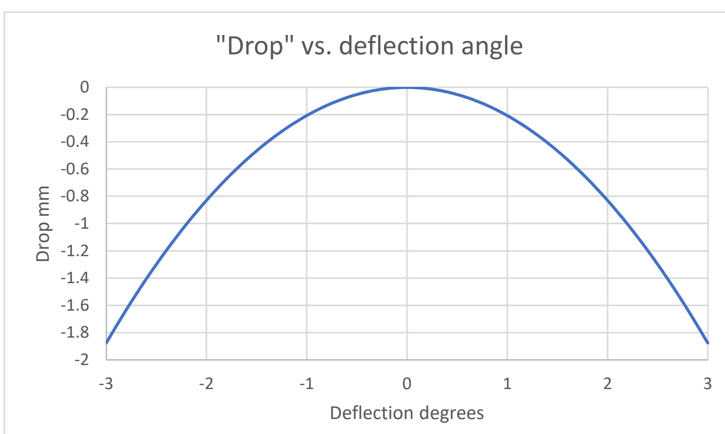


Figure 4: Drop vs. pendulum deflection

In operation, the output of the Hall sensor mounted at the end of the finial will be monitored by the control microprocessor. From the measurements on the sensor given above it can be seen that there will be a signal (a falling edge in fact) from the sensor after the impulse weight lift has started, when the bob is just 1.2mm before BDC; followed by a rising edge when the bob is 4mm after BDC. Given that the horizontal deflection is sinusoidal at an angular frequency of π radians/sec[1] with amplitude 3° the lift will start 0.11s before BDC and end 0.15s after. Using the same values, the Hall pulse starts just 6.5ms before BDC and ends 22ms after. If therefore the escapement magnet is energised by the *leading edge* of the Hall pulse it will have 0.11s to pull the Lifting Lever down before the Impulse Lever returns to the initial drop position.

The point in time where the magnet is released is less critical. Once the Lifting Lever is lowered it will catch the Cradle when it reaches the final drop position, and only needs to lift it before the next time the Impulse lever reaches the lift level, which is nearly one second later. Thus the control processor could turn the magnet off after perhaps 300ms.

We can conclude that a Hall Effect sensor will be sufficiently precise to trigger the control microprocessor to activate the impulse electromagnet, which can then be released after a fixed later delay, without affecting the impulse timing which is defined by the escapement geometry.

[1] Pendulum period=2 seconds