# HOW MANY TEETH SHOULD A HEALTHY GRASSHOPPER HAVE?



## INTRODUCTION

John Harrison’s final land-based, longcase, precision regulator, commonly referred to as the 'R.A.S. Regulator', is currently on deservedly prominent public display in The Harrison Gallery, Royal Observatory, Greenwich, England. Reportedly discovered in an incomplete state amongst Harrison’s possessions after his death in 1776, the regulator has been completed and restored more than once during the intervening centuries. Regrettably, a notable victim of careless work is the single pivot grasshopper escapement currently installed.

## OBJECTIVES

1. To offer evidence that the current R.A.S. Regulator escapement cannot possibly perform as Harrison must have intended.

2. To suggest viable corrective options.

## ADDITIONAL GUIDANCE – APPENDIX, CSM and PHSPGE

An Appendix offers abbreviated explanations of torque arm, torque ratio, Harrison’s escapement layout drawing MS3972/3 and component survival prospects.

‘Concerning Such Mechanism’ **(CSM)**, Harrison’s 1775 manuscript, is available from the NAWCC Horological Science website: http://www.hsn161.com/HSN/CSM.pdf Sincere thanks to Mr Peter Hastings for transcribing CSM and for his generosity in offering it freely to all.

‘Perfecting the Harrison Single Pivot Grasshopper Escapement’ **(PHSPGE)**, first published in 2009 as an extract from a larger work, is a detailed study of the Harrison single pivot grasshopper escapement. Including relevant explanations, phraseology, notation and full details of the mathematical design and manipulation tool upon which this study is largely based, it is available from the NAWCC Horological Science website: http://www.hsn161.com/HSN/Heskin.pdf

## STANDARDS AND NOTATION

All pendulums are seconds beating.
All escape wheels are of 120 teeth, forward rotating clockwise.
Escape wheel recoil is not considered (assumed to be nil).
Units: degrees and millimeters (deg and mm)

b The angle subtended by half an escape wheel tooth space.
AD Exit pallet arm, from locking corner to pivot, at the start of impulse.
BC Exit pallet arm, from locking corner to pivot, at the end of impulse, before release.
C Pallets pivot at the start of entry pallet impulse and the end of exit pallet impulse.
CJ Entry pallet arm, from pivot to locking corner, at the start of impulse.
CZ Separation of the escapement frame arbor axis (Z) and pallets pivot axis (C).
D Pallets pivot at the end of entry pallet impulse and the start of exit pallet impulse.
DK Entry pallet arm pivot to locking corner at the end of impulse, before release.
M Mean torque arm. The Appendix and PHSPGE explain this parameter.
n Mean number of escape wheel tooth spaces spanned by the escapement pallet nib locking corners. Alternatively 'teeth spanned' or 'span'.
O Escape wheel arbor axis.
OZ Separation of the escape wheel arbor axis (O) and escapement frame arbor axis (Z).
p Pendulum amplitude (arc), in degrees.
PCD Escape wheel teeth tips pitch circle diameter.
R Escape wheel teeth tips pitch circle radius.
t Mean torque ratio. The Appendix and PHSPGE explain this parameter. Assuming constant delivered force, mean torque ratio is equivalent to mean torque arm ratio.
V Entry pallet nib locking corner position after release
W Exit pallet nib locking corner position after release
Z Escapement frame arbor axis. The commonly used escapement term 'pallet arbor' is inappropriate and too easily confused with the grasshopper escapement 'pallets pivot'.

## CONCERNING SUCH MECHANISM (CSM)

In 1775, the year before his death, Harrison recorded much of his life's work in a remarkable, somewhat difficult and indisputably neglected manuscript entitled: *'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'*.

'Concerning Such Mechanism' or **'CSM'**, as it will be referred to, provides detailed stipulations for the design of timepieces adhering to Harrison's principles, including precise requirements for the form and performance of his grasshopper escapement, as follows:

- A four-minute (120 tooth) escape wheel must be used in combination with a seconds beating pendulum.

- The mean torque arm must be 1% of the length of a seconds beating simple pendulum for the intended location (therefore 9.94156 mm, for London).

- The mean torque ratio during one complete (two seconds) cycle must be two to three (0.666'). In fact, Harrison stated 'about as two' to three, although there can only be one sensible interpretation: *precisely* two to three (see PHSPGE for details).

# THE 'RAS22.5' ESCAPEMENT GEOMETRY

Information regarding the current R.A.S. Regulator escapement is scarce and photography and measurement are prohibited. It is, however, obvious from observation that the mean span of the pallets is 22.5 escape wheel tooth spaces (22 minimum, 23 maximum, 22.5 mean during one complete cycle).

Fortunately, some experience of estimating the dimensions of poorly documented and protected timepieces, largely from visual estimation, suggests that accessible features may often be assessed to within 2% of truth. Usefully, the separation of the R.A.S. Regulator escape wheel arbor, O and escapement frame arbor, Z is a particularly accessible dimension (the front dial clearly defines the location of the escape wheel arbor and the top edge of the rear main movement plate establishes the position of the axis of the escapement frame arbor). From observation, OZ has been estimated to be 84 mm. An escapement geometry has been derived from similar observation, common knowledge and logical deduction. **Figure 1** illustrates the estimated geometry and **Table 1** lists the parameters defining it. The geometry will be referred to as '**RAS22.5**' (the **RAS** Regulator being the basis, **22.5** the mean number of tooth spaces spanned).

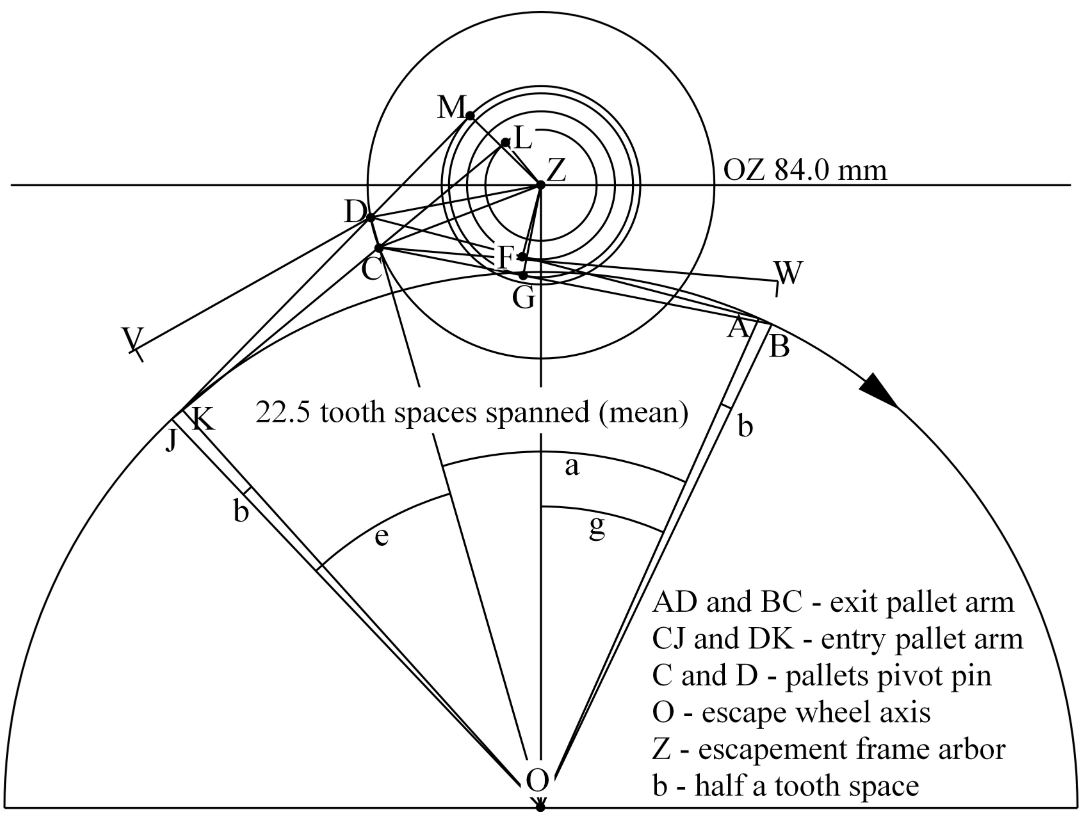


**Figure 1 - The RAS22.5 Escapement Geometry (estimated)**

| n | R | OZ | CZ | CJ | AD |
|---|---|---|---|---|---|
| 22.5 | 72.298 | 84.000 | 23.368 | 36.320 | 54.113 |

**Table 1 - The RAS22.5 Escapement Geometry (estimated, 3dp)**

The torque delivery characteristics of a grasshopper escapement geometry would, in normal circumstances, be of considerable value. Regrettably, the estimated RAS22.5 geometry cannot be relied upon to provide sufficiently precise information. Analysis will, therefore, be approached from an alternative direction, essential preparation for which will be completed in the next section.

## CSM COMPLIANT GRASSHOPPERS

Eight Harrison grasshopper escapement geometries have been derived from the mathematical model described in PHSPGE (briefly, the model, based upon Harrison's methods and stipulations, creates precise, optimised, CSM compliant grasshopper escapements). **Table 2** lists relevant parameters, to three decimal places, for ease of reference. The listed geometries all deliver a mean torque ratio, t, of two to three (0.666') at a mean torque arm, M, of 9.942 mm (3 dp).

It is vital to understand that CSM compliant geometries are unique. For a given number of mean tooth spaces spanned, no other geometry can be devised in compliance with Harrison's methods and every relevant stipulation. Put another way, if a grasshopper escapement geometry of a given span is compared to the geometry having the same span in Table 2, it can only be completely compliant with CSM if both geometries are of exactly the same form and size.

| n | R | OZ | CZ | CJ | AD | p | KV | BW |
|---|---|---|---|---|---|---|---|---|
| 23.5 | 106.500 | 131.614 | 17.362 | 71.149 | 79.541 | 15.932 | 23.712 | 18.256 |
| 22.5 | 100.482 | 122.238 | 18.006 | 62.949 | 71.498 | 15.035 | 20.458 | 14.929 |
| 21.5 | 94.668 | 113.550 | 18.712 | 55.454 | 64.190 | 14.167 | 17.654 | 12.065 |
| 20.5 | 88.946 | 105.381 | 19.486 | 48.544 | 57.488 | 13.310 | 15.214 | 9.578 |
| 19.5 | 83.360 | 97.753 | 20.335 | 42.199 | 51.384 | 12.470 | 13.106 | 7.442 |
| 18.5 | 77.830 | 90.556 | 21.266 | 36.340 | 45.792 | 11.635 | 11.274 | 5.603 |
| 17.5 | 72.278 | 83.696 | 22.281 | 30.903 | 40.644 | 10.793 | 9.670 | 4.022 |
| 16.5 | 66.655 | 77.118 | 23.380 | 25.849 | 35.896 | 9.936 | 8.260 | 2.676 |

**Table 2 – CSM Compliant Escapement Geometries (computed, 3dp)**

## THE 'CSM22.5' ESCAPEMENT GEOMETRY

A CSM compliant geometry spanning 22.5 tooth spaces, referred to herein as '**CSM22.5**' (**CSM** being the basis, **22.5** the mean number of tooth spaces spanned) is highlighted in Table 2 and illustrated in **Figure 2**, drawn to the same scale as RAS22.5 of Figure 1.

## RAS22.5 AND CSM22.5 COMPARED

From a comparison of Figure 1 (RAS22.5) and Figure 2 (CSM22.5), it is immediately obvious that, however poor the estimation of RAS22.5 might be, it cannot possibly account for the considerable differences between the two geometries, spanning the same number of tooth spaces. There can, therefore, be absolutely no doubt that RAS22.5 must fail to comply with CSM.

**First Conclusion:** There can be no doubt that the current R.A.S. Regulator escapement, spanning 22.5 tooth spaces, is not as Harrison would have demanded in 1775, for the escapement certainly fails to comply with his CSM stipulations, published in that year. This conclusion achieves the first objective of the opening page.

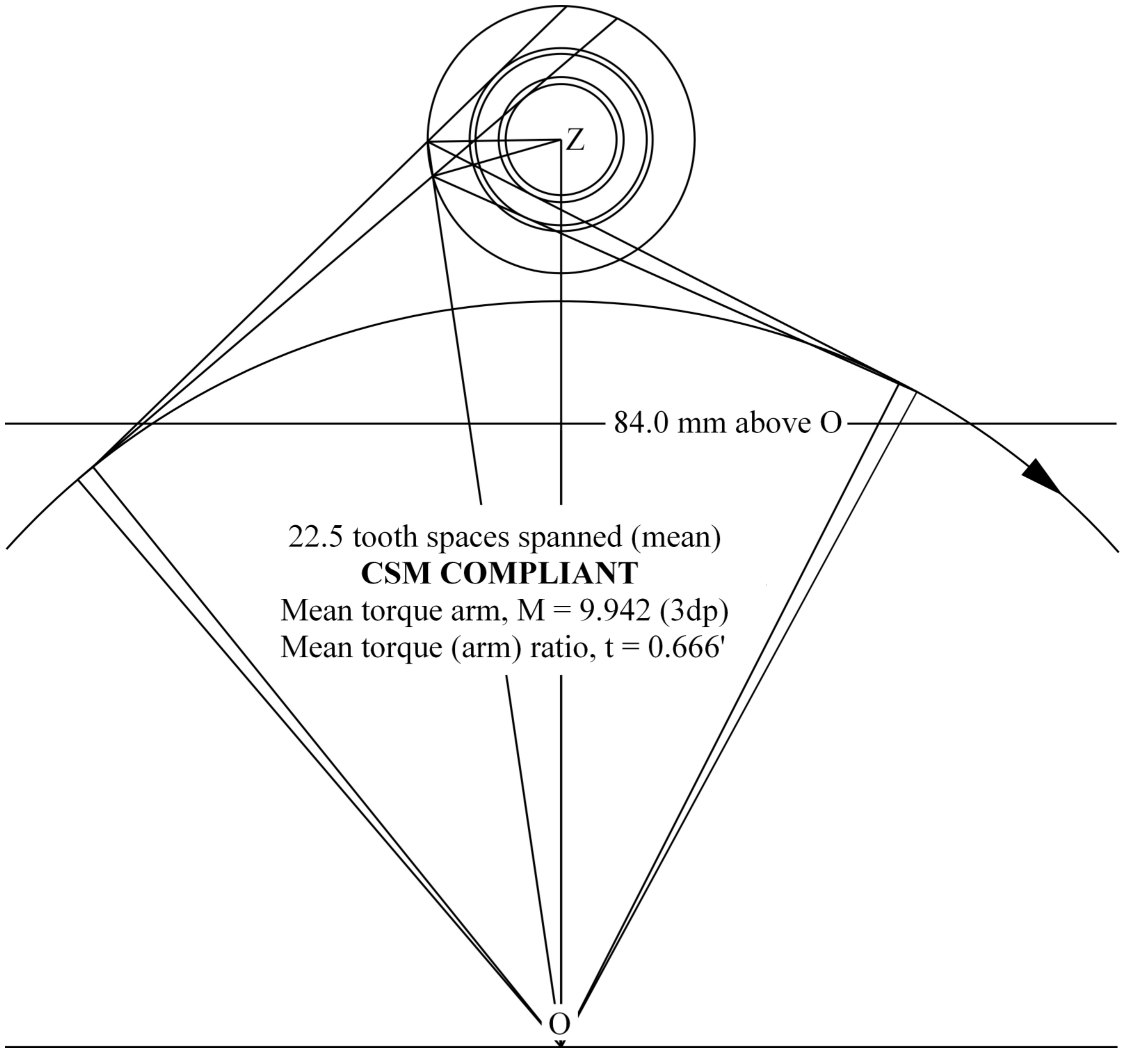


**Figure 2 - The CSM22.5 Escapement Geometry (computed)**

## THE R.A.S. REGULATOR AND CSM22.5 COMPARED

CSM22.5, despite offering perfect compliance with Harrison's stipulations, would be an unsuitable fitment for the R.A.S. Regulator. For example, CSM22.5 dimension OZ, the arbor separation, is 122.238 mm and is, therefore, markedly incompatible with the estimated R.A.S. Regulator arbor separation of 84.000 mm. It is inconceivable that that the 84.000 mm estimation could be sufficiently in error to permit the accommodation of 122.238 mm.

All CSM22.5 linear dimensions could be 'scaled to fit', by the ratio [OZ for RAS22.5] divided by [OZ for CSM22.5]. Unfortunately, that would also reduce the mean torque arm of the escapement in proportion, thereby violating, to a considerable degree, Harrison's stipulation for mean torque arm.

**Second Conclusion:** A 22.5 tooth space span, CSM compliant grasshopper escapement is incompatible with the R.A.S. Regulator movement.

## THE R.A.S. REGULATOR AND CSM17.5 COMPARED

In pursuit of an acceptable, CSM compliant, escapement for the R.A.S. Regulator, inspection of Table 2 reveals a striking potential compatibility. The arbor separation, OZ, for 17.5 tooth spaces spanned is 83.696 mm, similar to the estimated R.A.S. Regulator OZ of 84.000 mm. The arbor separations of any remaining CSM compliant escapements in Table 2 are certainly incompatible with the R.A.S. Regulator, by considerable margins, worsening as the departure from 17.5 tooth spaces spanned increases. **Figure 3** illustrates the **'CSM17.5'** geometry (**CSM** being the basis, **17.5** the span).

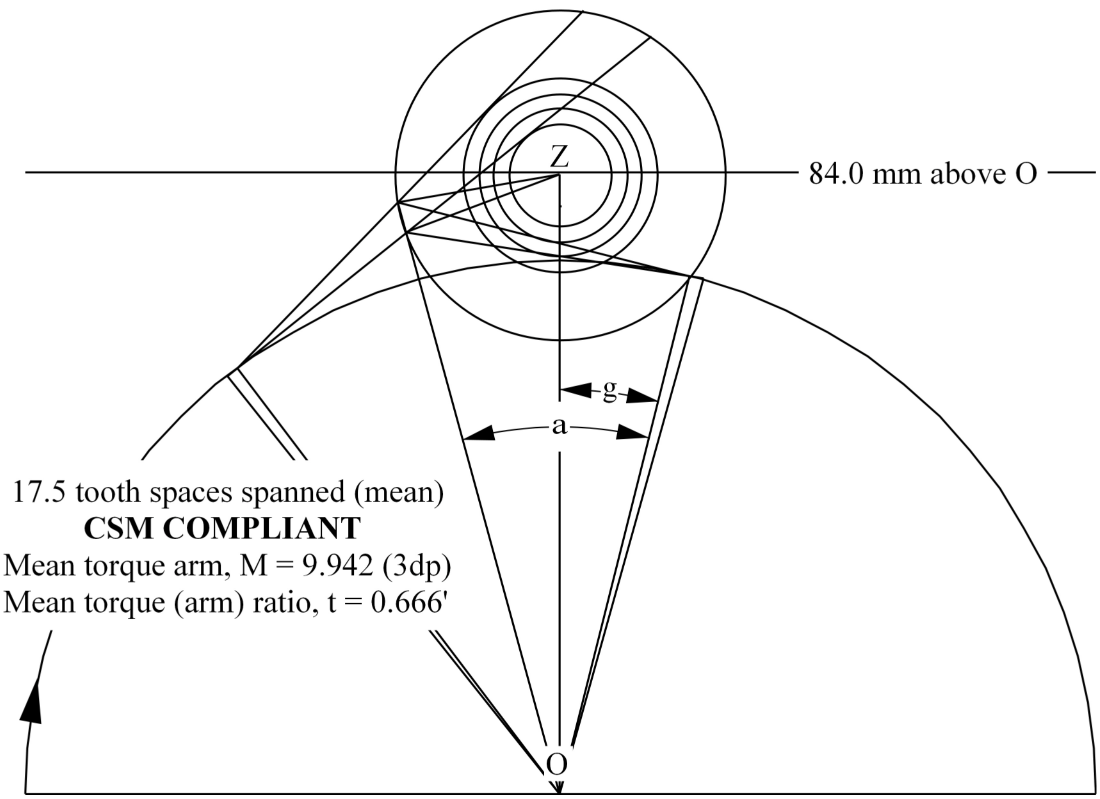


**Figure 3 - The CSM17.5 Escapement Geometry (computed)**

**Third Conclusion:** A CSM compliant escapement geometry spanning 17.5 tooth spaces is the only compliant geometry potentially compatible with the R.A.S. Regulator.

Comparison of RAS22.5 and CSM17.5 (see **Table 3)** reveals similarities in OZ, CZ and R, but a considerable difference in the lengths of the exit pallet arms (AD) and a moderate difference in the lengths of the entry pallet arms (CJ).

| | n | R | OZ | CZ | CJ | AD |
|---|---|---|---|---|---|---|
| **RAS22.5** | 22.5 | 72.298 | 84.000 | 23.368 | 36.320 | 54.113 |
| **CSM17.5** | 17.5 | 72.278 | 83.696 | 22.281 | 30.903 | 40.644 |

**Table 3 – The R.A.S. Regulator (RAS22.5) and CSM17.5 Compared**

At some point in the history of the R.A.S. Regulator, it appears likely that an inappropriate span of 22.5 tooth spaces has been incorporated entirely by extending the pallet arms, whilst retaining the arbor separation, escapement frame and escape wheel of an escapement spanning 17.5 tooth spaces. The assumption of estimated dimensions must never be forgotten, although the conclusion would, almost certainly, not be altered by precise measurement of the R.A.S. Regulator escapement.

**Fourth Conclusion:** It is likely that the current R.A.S. Regulator escapement was originally constructed as an escapement spanning 17.5 tooth spaces, but was subsequently fitted with replacement pallet arms of markedly greater length, spanning an inappropriate 22.5 tooth spaces.

## UNITING THE R.A.S. REGULATOR AND CSM17.5

It is not impossible that the arbor separation (OZ), escapement frame arbor to pallets pivot (CZ) and escape wheel pitch circle radius (R) of the computer generated CSM17.5 geometry would simultaneously match the current R.A.S. Regulator component dimensions precisely. It would, however, be of little surprise if there were disagreements, given that Harrison would have designed the geometry graphically, incorporating inevitable inaccuracies in iteration, drawing and measurement. However, should there be any differences, it would be inadvisable to ignore them, however apparently insignificant they might seem to be, in an effort to preserve existing components. The grasshopper escapement can be extremely intolerant (in terms of correct functioning) of any deviations from an absolutely correct geometry.

Suitable scaling of the CSM17.5 geometry would at least ensure compatibility with the current locations of the escape wheel arbor (O) and the escapement frame arbor (Z), for the alteration of either location would be too disruptive to contemplate. Unfortunately, any scaling would also cause a deviation from the CSM stipulation for mean torque arm.

**Fifth Conclusion:** Should any R.A.S. Regulator component dimensions differ from the corresponding CSM17.5 dimensions, installation of CSM17.5 would necessitate the replacement or modification of those R.A.S. Regulator components.

## PRESERVATION - THE R.A.S. REGULATOR AND DEV17.5

As a potentially less destructive alternative to CSM17.5, this section will describe the creation of a 17.5 span grasshopper escapement intentionally deviating from CSM. It will, no doubt, seem strange that, having invested time and effort in the successful creation of a perfectly optimised grasshopper escapement geometry, there should now be a deliberate attempt to spoil that achievement. However, the R.A.S. Regulator is no longer an experimental prototype, for which optimum performance is the highest priority, it is a priceless, centuries-old timekeeper. *The higher priority must be preservation.* Of course, the logical and sound extension of that argument is that the existing escapement, complete with ridiculous pallet arms spanning too many teeth, should be retained. *There will be no disagreement.* Nevertheless, bearing in mind the susceptibility of grasshopper escapement pallet arms to accidental damage (see 'Survival Prospects' in the Appendix), the following analysis may be of future value. If nothing else, it might be an interesting exercise in the unusual techniques of grasshopper escapement geometry design and manipulation.

**DEV17.5** will be a geometry **DEV**iating from CSM, spanning **17.5** tooth spaces.

## CREATING DEV17.5 – PRINCIPLES

**Step 1. Establish preservation priorities**

The first task is to allocate preservation priorities to the components constituting the current R.A.S. Regulator escapement geometry. The following list is derived from the comments presented in 'Survival Prospects', in the Appendix.

In decreasing order of preservation priority:

i. Escape wheel arbor & escapement frame arbor supports (defined by the arbor separation, OZ)

ii. Escapement frame (defined by the pallets pivot to escapement frame arbor separation, CZ)

iii. Escape wheel (defined by the pitch circle radius, R)

iv. Entry pallet arm (defined by the pivot to locking corner separation, CJ)

v. Exit pallet arm (defined by the pivot to locking corner separation, AD)

**Step 2. Select two components to be preserved**

At this point a major constraint must be introduced: it is only possible to distort a grasshopper geometry with a maximum of *two* dimensions as simultaneous targets.

It is, for example, possible to incorporate distortions such that a target dimension **OZ** and a target dimension **CZ** are simultaneously achieved within the same geometry. Having achieved those two objectives, it would not then be possible to deliberately achieve a target R, a target CJ, a target AD, or any target combination of those three dimensions.

As another example, it is possible to incorporate distortions such that a target dimension **OZ** and a target dimension **R** are simultaneously achieved within the same geometry. Having achieved those two objectives, it would not then be possible to deliberately achieve a target CZ, a target CJ, a target AD, or any target combination of those three dimensions.

It is unlikely (although, obviously, possible) that pairings of OZ and CJ, or OZ and AD would be chosen, given that the replacement of pallet arms (defined by CJ and AD) is a relatively straightforward task, that the pallet arms are the most likely components to have been replaced in the past and that they are, therefore, least likely to be original Harrison components.

*** For simplicity, it will be assumed that OZ and CZ are the component dimensions to be preserved.

**Step 3. Manipulate the PHSPGE Mathematical Model**

The creation of DEV17.5 requires that the mathematical model presented in PHSPGE be manipulated, which, obviously, requires an understanding of the relevant explanations provided therein. In addition, the technique described below must be applied.

A sensible and obvious starting point is the CSM17.5 geometry (Figure 3 and Table 3). Appropriate distortion of CSM17.5 must then be performed, until the geometry has been transformed into the necessary DEV17.5 geometry, incorporating the two chosen target dimensions to be preserved. In an effort to ease the process, seeking a *target ratio* of the two dimensions to be preserved will reduce the targets from two to one and avoid intermediate scaling operations. Having chosen to preserve OZ and CZ (see***), the chosen target ratio will be OZ / CZ (although CZ / OZ is a no less valid alternative).

Adjustment of 'g' will alter all four torque arms. In this application, the useful effect will be related alterations in the target dimensions OZ and CZ (and, therefore, the target ratio, OZ / CZ). The *undesirable* effect will be a departure from CSM stipulations for mean torque (arm) ratio and mean torque arm. Obviously, in suitable situations, mean torque arm could be restored to the CSM stipulation by scaling. In this application, however, arbor separation, OZ, will dictate the scale of the geometry and the consequent mean torque arm deviation from CSM must be accepted.

Following the creation of a suitable DEV17.5 geometry, a check should be made for any departure from what will be referred to as 'matching'. Matching of a grasshopper escapement ensures that either pallet nib locking corner will engage precisely with the relevant escape wheel tooth tip at the appropriate stage in the escapement cycle. The escapement will then operate correctly throughout continuous cycling of the escapement. The starting point for the iteration, CSM17.5, has already been adjusted for perfect matching, although the effects of reduction to 3 decimal places for ease of presentation would demand a fresh mathematical construction for any future analyses. **Angle 'a'** (see Figure 3) is the controlling parameter. Note that any adjustment of 'a' will necessitate a subsequent readjustment of 'g'.

Finally, the geometry is scaled, in order to achieve an arbor separation, OZ, matching that of the intended movement, in this case the R.A.S. Regulator.

The following example, targeting the RAS22.5 (estimated) dimensions for OZ and CZ, should clarify the process.

## CREATING DEV17.5 - EXAMPLE

**Step 1. Determine preservation priorities**

The priorities listed earlier as i. to v. will be adopted.

**Step 2. Select two components to be preserved**

Arbor locations (i.e. arbor separation OZ) and escapement frame arbor to pallets pivot (CZ).

The target ratio will be OZ / CZ.

**Step 3. Manipulate the PHSPGE Mathematical Model**

All to three decimal places, millimetres and degrees. Iteration steps not shown.

**(i) - Existing (estimated) R.A.S. Regulator dimensions. From Table 1. Illustrated in Figure 1.**

| | | | |
|---|---|---|---|
| **OZ** | **=** | **84.000** | **Target dimension** |
| **CZ** | **=** | **23.368** | **Target dimension** |
| R | = | 72.298 | |
| CJ | = | 36.320 | |
| AD | = | 54.113 | |

| | | |
|---|---|---|
| Target OZ/CZ | = | 84.000/23.368 |
| **Target OZ/CZ** | **=** | **3.595** |

**(ii) - CSM17.5 geometry. Perfectly matched. From Table 2 ( 3dp). Illustrated in Figure 3.**

| | | | |
|---|---|---|---|
| Input g | = | 13.981 | Input of this 'g' achieves CSM 't' compliance |
| OZ | = | 83.696 | |
| **t** | **=** | **0.666'** | **CSM compliance** |
| **M** | **=** | **9.942** | **CSM compliance, London** |
| Output OZ/CZ | = | 3.756 | |
| Target OZ/CZ | = | 3.595 | |
| OZ/CZ difference | = | +0.161 | |
| CZ | = | 22.281 | |
| R | = | 72.278 | |
| CJ | = | 30.903 | |
| AD | = | 40.644 | |

**(iii) - CSM17.5 geometry, after scaling to achieve OZ = 84.00 (<u>not essential, for clarity only</u>)**

| | | | |
|---|---|---|---|
| Input g | = | 13.981 | No change |
| OZ | = | 84.000 | CSM17.5 scaled by 84.000/83.696 |
| t | = | 0.666' | CSM compliance. No change |
| M | = | 9.978 | CSM17.5 scaled by 84.000/83.696. **CSM deviation** |
| Output OZ/CZ | = | 3.756 | No change |
| Target OZ/CZ | = | 3.595 | No change |
| OZ/CZ difference | = | +0.161 | No change |
| CZ | = | 22.362 | CSM17.5 scaled by 84.000/83.696 |
| R | = | 72.541 | CSM17.5 scaled by 84.000/83.696 |
| CJ | = | 31.015 | CSM17.5 scaled by 84.000/83.696 |
| AD | = | 40.792 | CSM17.5 scaled by 84.000/83.696 |

**(iv) - Iteration performed (not shown), altering 'g' to seek the target OZ/CZ of 3.595**

**(v) - DEV17.5 geometry, after iteration completed, before scaling.**

| | | | |
|---|---|---|---|
| **Input g** | **=** | **13.269** | **Input of this ‘g’ achieves the target OZ/CZ of 3.595** |
| OZ | = | 84.295 | Altered by the change in ‘g’ during the iteration |
| t | = | 0.679 | CSM deviation introduced. |
| M | = | 10.468 | CSM deviation still |
| Output OZ/CZ | = | 3.595 | Target achieved |
| Target OZ/CZ | = | 3.595 | No change |
| **OZ/CZ diff.** | **=** | **0.000** | **Target OZ/CZ achieved** |
| CZ | = | 23.450 | Altered by the change in ‘g’ during the iteration |
| R | = | 72.541 | No change, because scaling has yet to be applied. |
| CJ | = | 31.015 | No change, because scaling has yet to be applied. |
| AD | = | 40.792 | No change, because scaling has yet to be applied. |

**(vi) - Perfect matching is confirmed, see PHSPGE. Therefore, no requirement to alter ‘a’**

**(vii) - DEV17.5 geometry, after scaling to achieve OZ = 84.00. Illustrated in Figure 4**

| | | | |
|---|---|---|---|
| Input g | = | 13.269 | No change |
| **OZ** | **=** | **84.000** | **Scaled by 84.000/84.295. Now as intended** |
| **t** | **=** | **0.679** | No change. **Not CSM** |
| **M** | **=** | **10.431** | Previous geometry scaled by 84.000/84.295. **Not CSM** |
| Output OZ/CZ | = | 3.595 | No change |
| Target OZ/CZ | = | 3.595 | No change |
| OZ/CZ difference | = | 0.000 | No change |
| CZ | = | 23.368 | Previous geometry scaled by 84.000/84.295 |
| R | = | 72.287 | Previous geometry scaled by 84.000/84.295 |
| CJ | = | 30.906 | Previous geometry scaled by 84.000/84.295 |
| AD | = | 40.649 | Previous geometry scaled by 84.000/84.295 |

**Figure 4** illustrates DEV17.5 for the two achieved targets of OZ = 84.000 and CZ = 23.368. The similarity with CSM17.5 (Figure 3) is hardly surprising, given that one is derived from the other by virtue of only mild adjustments to angle ‘g’ (just over 0.7 degrees, or 5.1 % less). There have been alterations to mean torque arm (4.9 % increase) and mean torque (arm) ratio (1.95 % increase). Measured dimensions, rather than estimations, would probably generate different results, but the described method and any derived conclusions would be completely unaltered.

An earlier suggestion, that Harrison designed the geometry graphically, thereby incorporating inaccuracies in iteration, drawing and measurement, is worthy of recall at this point. The incorporation of estimated RAS22.5 dimensions should also be borne in mind. It is quite possible that Harrison attempted to create a design complying with CSM (i.e. CSM17.5), but that the aforementioned inaccuracies caused distortions to the geometry and deviations from the ideal. A logical extension of that suggestion is that the R.A.S. Regulator arbor separation, escapement frame and escape wheel would have been constructed in accordance with the distorted geometry. That would explain any future incompatibility between the R.A.S. Regulator and the ideal of CSM17.5.

In a perfect world, there would be no doubt that CSM17.5, offering ideal CSM compliance, would be the escapement geometry of choice for the optimum Harrison longcase regulator. In our imperfect world, second best may demand our acceptance. If nothing else, this study offers either option, thus achieving the second objective of the opening page.

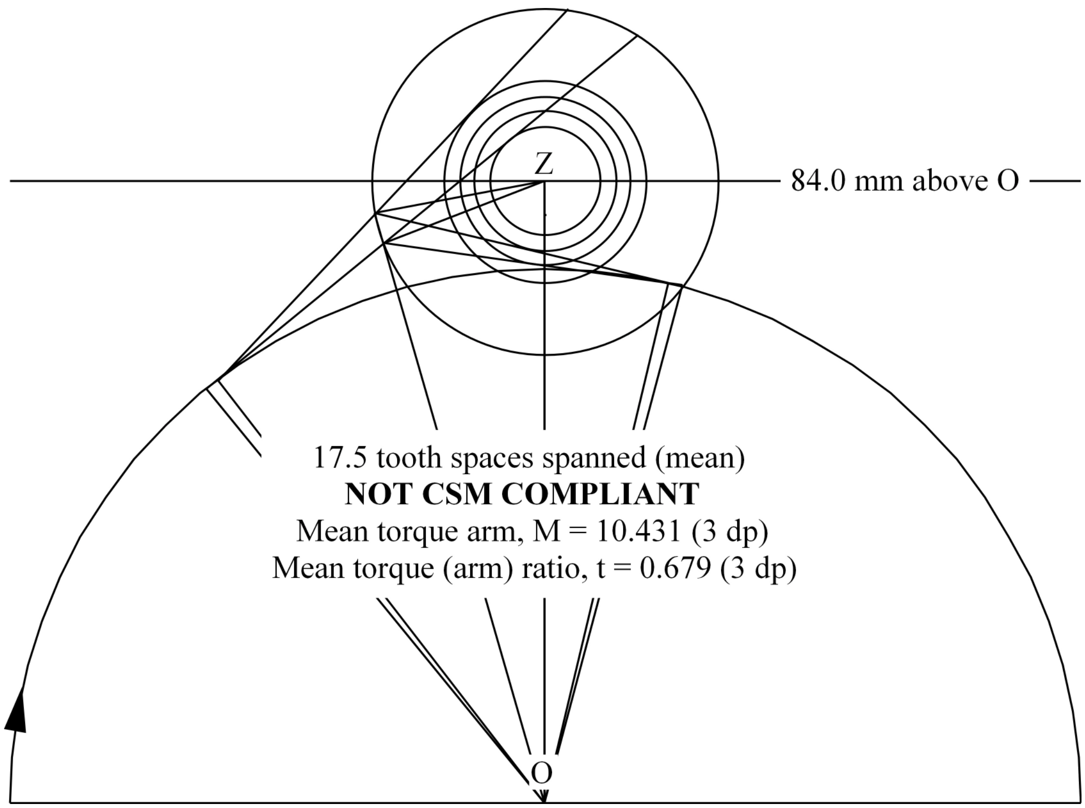


**Figure 4 - The DEV17.5 Escapement Geometry (computed)**

## APPENDIX

In order, to some extent, to present a self-contained publication within limited size constraints, condensed descriptions and explanations of relevant topics are offered.

## TORQUE ARMS

A pallet torque arm is the radius of a circle, centred at the axis of the escapement frame arbor (Z), to which the line of action of the applicable pallet arm is a tangent (shown as perpendiculars LZ, MZ, FZ and GZ in Figure 1). When displaying grasshopper escapement geometries, it is enlightening to construct four circles, referred to as ‘torque arm circles’ or ‘torque circles’, centred at Z, each with radius equal to the applicable torque arm.

If LZ and MZ are the entry pallet torque arms at the start and end of impulse respectively and FZ and GZ are the exit pallet torque arms at the start and end of impulse respectively, then:

Mean torque arm M = (LZ+MZ+FZ+GZ) / 4

## MEAN TORQUE (ARM) RATIO

Torque (arm) ratio is a valuable measure of the development of impulse during pallet nib capture.

Torque (arm) ratio for the entry pallet t1 = LZ / MZ
Torque (arm) ratio for the exit pallet t2 = FZ / GZ
Mean torque (arm) ratio t = (t1 + t2) / 2

Assuming constant impulse forces along either pallet arm during one cycle, the mean torque ratio equals the mean torque arm ratio. PHSPGE describes the small corrections to be applied should force variation along the pallet arms require incorporation. For the purposes of this publication, no corrections were necessary.

## MS3972/3

An untitled, sparsely annotated, enigmatic and arguably ambiguous escapement layout drawing, catalogued by The Worshipful Company of Clockmakers as ‘MS3972/3’, includes four geometries, one of which, spanning 17.5 teeth, is regarded by some to be Harrison’s geometrical design drawing for the R.A.S. Regulator escapement.

The original drawing is almost certainly to a scale of one-to-one, which would be a poor choice for constructing a geometry markedly intolerant of inaccuracies. Harrison would, surely, have drawn his geometrical construction to a much larger scale, measured the derived dimensions and reduced them to a scale of one-to-one, in an effort to minimise iteration, drawing and measurement errors and achieve precise matching. Slight errors in design are perfectly capable of causing incorrect grasshopper escapement operation (mismatch) not to mention deviations from CSM torque delivery stipulations.

Harrison’s MS3972/3 layout incorporates geometrical flaws that may well prevent correct operation (mismatch). *The mean torque (arm) ratio and mean torque arm deviate from CSM.* Admittedly, available copies of the drawing all appear to suffer non-linear distortions, rendering analysis difficult.

In conclusion, if MS3972/3 was indeed used by Harrison as the sole basis for the design of the R.A.S. Regulator escapement geometry, it would be of little surprise if many details, including the arbor separation, OZ, deviated from the perfect form defined by CSM17.5. Was the drawing merely an aide-mémoir?

Despite the previous comments, MS3972/3 is, nevertheless, of immeasurable value in some respects. Of greatest significance, the span of one construction is 17.5 tooth spaces and the line of action of each pallet arm is tangential to the escape wheel at the start of impulse. Recognition of the latter feature was vital to an understanding of Harrison’s intentions and methods and the creation of the analytical techniques presented in PHSPGE.

## SURVIVAL PROSPECTS

For the purposes of focused analyses, it is useful to assign probabilities of survival to the individual escapement components. Detailed opinions and experiences may vary, but the general conclusions are nothing more than common sense.

In order of worsening survival prospects:

**1. Arbor Separation**

Of the current R.A.S. Regulator escapement features, the escapement frame arbor and escape wheel arbor locations are the most certain to have been completed by Harrison, unaltered during restorations and undamaged due to mishandling. No restorer, regardless of his or her level of competence, could have justified a deliberate alteration of the arbor separation. The features most vulnerable to damage and replacement are the four anti-friction wheels supporting the escape wheel arbor. The slightest damage to a wheel periphery can prevent correct functioning, demanding replacement. A temptation might be to 'repair' a wheel by removing material from the periphery, creating a slightly smaller diameter and thereby altering the arbor axis location. Fortunately, the arbor front end stop is affixed to the main dial, thus revealing any front anti friction wheel reduction(s). Alteration to the rear antifriction wheels would tilt the large diameter escape wheel, causing obvious misalignment and/or conflict with adjacent bridges. The arbor separation can, therefore, be safely assumed to be original

**2. Escapement Frame**

The escapement frame, defined by dimension CZ (Figure 1), would be difficult to damage to an extent requiring replacement, either during excessive pendulum excursion, escapement trip and runaway, or during adjustment. Undetectable modification of the escapement frame arbor and pallets pivot pin separation (CZ) would be difficult to conceal, requiring relocation of the arbor and/or the pin and infill of the redundant hole(s). It is unlikely that any restorer would suspect that the frame was responsible for a failure of the escapement to function and subject it to 'remedial' alteration.

It may be useful to observe that the escapement frame is fairly ornate and surprisingly complex in construction and form. The decorative frame counterbalance is a separate brass insert, with a piercing lead weight, attached to a frame of difficult profile, obviously demanding a fair investment of skill and time in its construction. Such features, arguably, suggest originality and could, perhaps, have discouraged replacement.

**3. Escape Wheel**

Defined by dimension 'R' (or OA, OB, OJ and OK, Figure 1). Damage due to escapement 'trip' and 'runaway' (see 5. for a detailed description) is the most likely reason for replacement, although the brass escape wheel is more resistant to irreparable damage than the wooden pallet arms and nibs. Complete replacement of the escape wheel would introduce a possibility of manufacture to an incorrect pitch circle diameter (PCD) of the teeth tips. The PCD of a comprehensively damaged escape wheel might be difficult to measure accurately, thereby introducing an error. Correct manufacture, finishing and inspection of escape wheel teeth requires some care, lest the PCD be unintentionally altered. Nevertheless, a replacement escape wheel of simple form would hardly be difficult to manufacture. There is no scope for any modification of the teeth. The likelihood of healthy escape wheel replacement, due to a failure of the escapement to function, is low.

## 4. Entry Pallet Arm

Defined by dimension CJ (and DK), Figure 1. Comments for the exit pallet arm apply (see below), except to add that there is a lesser risk of damage to the entry arm during escapement trip and escape wheel runaway, due to the nib being in the path of the escape wheel for a lesser proportion of the pendulum amplitude.

## 5. Exit Pallet Arm

Defined by dimension AD (and BC), Figure 1. The exit pallet arm, most especially the nib, is by far the most vulnerable component in the entire escapement (nay, the entire regulator). The most frequent cause of damage to grasshopper escapements is the simultaneous disengagement of both pallet arm nibs from the escape wheel ('trip'), permitting high-speed rotation ('runaway') and subsequent impact between speeding escape wheel teeth and nibs, as the pendulum and/or the arms continue, or recover from, their motions prior to escapement trip. Incompetent or careless regulator winding, inaccurate manufacture and/or poor adjustment are common causes of trip, runaway and damage. The more likely victim of runaway is the exit pallet nib, by virtue of lying within the path of the escape wheel teeth for a far greater proportion of the pendulum amplitude than the entry pallet nib.

Wood is stronger along the grain than across the grain, which dictates that the grain of wooden pallet arms must necessarily lie along their length, in order to transmit impulse without breakage. The cross-grained nibs are, therefore, severely vulnerable to fracture during any impact with escape wheel teeth possessed of sufficient energy. Some wood species are stronger and/or more resilient than others, although the better the resistance to destruction of the nib, the greater the risk of damage to the more 'valuable' escape wheel teeth.

Pallet arms are vulnerable to unnecessary modification, for it is surprisingly easy to induce mismatch in a perfectly healthy grasshopper escapement, by incorporating slightly incorrect settings. The first target for ignorant 'improvement' would probably be the pallet arms. Such modification is of limited scope, in that the 'obvious' adjustment is a removal of material at the nib, rapidly leading to excessive weakening.

Depending upon the intricacy of the carving, a damaged pallet arm is fairly easily duplicated, provided that all broken fragments are available and the pivot to locking corner separation is accurately measured. The greatest danger of incorrect manufacture arises when broken pieces are missing to the extent that the original active length of the arm is uncertain. 17.5 tooth spaces spanned could thereby become 22.5, perhaps?