Clock mainspring sizing

A design approach based upon statistical analysis

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Introduction

A spring-driven clock's energy and hence power requirement has always been something of a mystery to me, and there are so many variables that I have found it impossible to undertake a classical scientific analysis. To do so would require a knowledge of the yield strength of the mainspring, and the change in strain in each mainspring coil between the fully wound and fully unwound condition, the latter being beyond the writer to calculate.

So, with the development of statistical analysis techniques made possible by the huge computing power available since the end of the 19th Century, I investigated what could be predicted from the successful clocks which I have serviced over the last fifteen years for which I had recorded basic mainspring data.

The clocks for which I had data were all 8-day clocks, and were divided into three groups:

- 18 in number with going barrel platform escapements,
- 44 with going barrel pendulum escapements, and
- 17 with fusee pendulum escapements.

Energy storage density

By comparison with other energy storage devices, the ability of a barrel-wound mainspring to store energy is pretty poor. For example, a lithium-ion battery can store up to 2500 kJ/litre, whereas even the best C21st watch mainspring can only store around 3 kJ/litre.

How much energy a mainspring can store or (more importantly) deliver will primarily be a function of the net barrel volume available for the mainspring to unwind from fully wound to fully unwound. To a first approximation, this can be represented by D^2h, where D = barrel diameter and h = mainspring height.

Energy storage is further affected by the yield strength of the mainspring steel, there being a huge energy storage difference between a low-yield 19th Century steel and late 20th Century high-yield steel. Mainspring thickness and length is not included; assuming the mainspring is reasonably optimised for the barrel diameter and going period of the clock, these dimensions will fall out of the subsequent design calculations.

Energy demands

The other question is what measure of the clock's size to use, and I chose the diameter of the chapter ring on the basis this would give some indication of the likely train friction demands (pivot diameters, etc.) and the weight of the hands. Strike work was generally present, but other complications were not. Other aspects such as balance wheel diameter, pendulum size and amplitude, bearing type (jewel, ball, etc.) were also ignored.

Ideally, the writer would have measured the energy delivered by each of these clocks, but this is not realistic in a servicing situation, as to do so would mean measuring the delivered torque at the winding square of each clock and mathematically integrating it over the running period.

Statistical analysis

Figure 1 gives an indication of the variation in required mainspring size based on the date of manufacture of the clock. The overall data fit is pretty poor (the solid black line), and all I can do is suggest it is better than nothing.

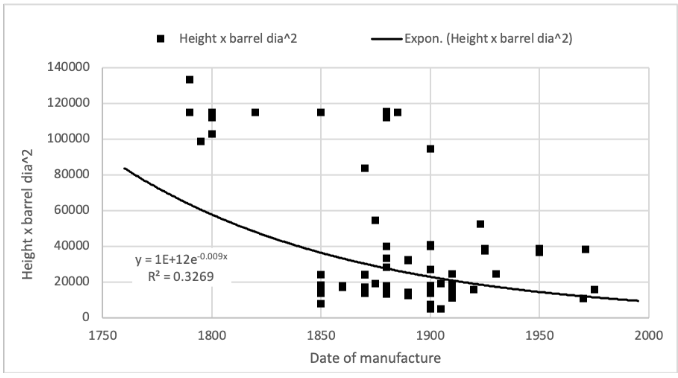

Figure 1: The increasingly compact mainsprings powering clocks of more recent manufacture

Figure 2 is a plot of the three groups of data. The data fit (R-squared value) for the fusee clocks is not good, but as the fusee is largely of historical interest only, I shall now set it aside*.

* The larger fusee clock barrel volumes were needed to deliver the necessary energy from the very low yield mainspring steels available at the time the clocks were designed. Those constructing replica fusee clocks will not have optimisation high on their list of priorities, and will always have more than enough barrel volume to allow for de-tuning of a modern mainspring.

The data fit in the other two groups is better, so does give an indication of the mainspring size needed to power a clock.

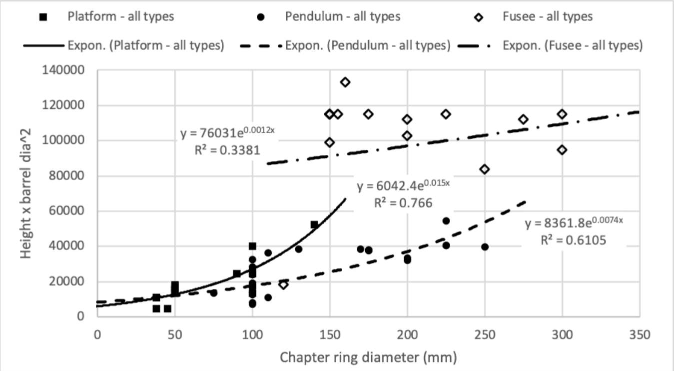

Figure 2: Barrel dimensions for three types of 8-day clock

The two going-barrel curves indicate that, for clocks with larger dials, the platform escapement appears to demand more energy than a pendulum escapement. This is perhaps in accordance with our observed experience, proportionally larger platform escapements rarely being found (if at all) in clocks with chapter rings greater than 125 mm diameter.

Using the Microsoft *Excel* exponential curve-fit function (Annexe A), one can fit mathematical equations to the going-barrel data sets in Figure 2:

Platform escapement: $h.D^2 \approx 6040.e^{0.015.CRD}$

Pendulum escapement: $h.D^2 \approx 8360.e^{0.007.CRD}$

where h = mainspring height,
D = barrel inside diameter, and
CRD = chapter ring diameter.

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Translating these equations into nominal going barrel dimensions for clocks with 75 mm and 100 mm diameter chapter rings results in Figure 3. These dimensions seem to correlate well with general experience for clocks manufactured before the mid-20th century on which, the data set is primarily based.

As a rough check, the mean $h.D^2$ of my collected data (41,156 mm^3) was compared with the mean $h.D^2$ calculated from the catalogued commercial mainspring data (37,141 mm^3) previously reported at reference A. Being within 10% and on the basis that requisites' suppliers will not stock unwanted sizes of mainspring, it perhaps gives some confidence in the validity of my approach.

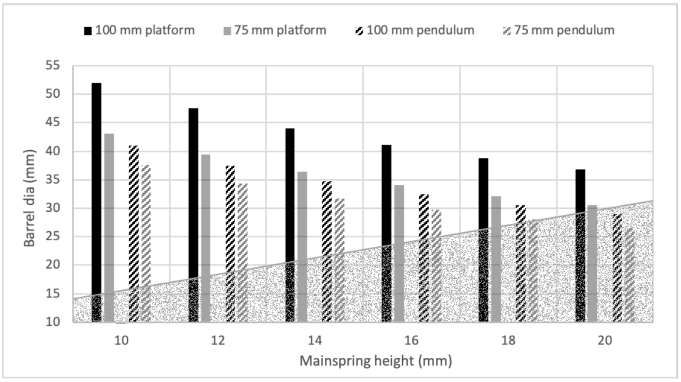

Figure 3: Calculated barrel dimensions for 8-day platform and pendulum clocks with 75 and 100 mm diameter chapter rings

Selecting the correct size barrel

Superficially, this design task is now relatively easy, the barrel size being determined primarily from dimensional constraints within the movement. However, the barrel diameter should be larger than the barrel height in order to minimise volumetric losses caused by hooking which, based on the ratios from the available data, is rarely below 1.5:1 (ie. the greyed area of Figure 3 should be avoided).

Barrel volumes selected using the aforementioned equations do depend upon the efficient use of the internal volume, which are primarily based upon:

- The arbor diameter being 1/3 of the barrel diameter,
- The spring thickness being 1/40 of the arbor diameter,
- The mainspring length being selected for optimum fill,
- Mainspring hooking being designed to minimise loss of available barrel volume,
- The gearing ratio between barrel and centre arbor being selected to give an 8-day going period from the available number of mainspring turns, and
- The steel having a yield strength not less than 700 MPa in its quenched and tempered condition (typical of all currently-available replacement mainsprings).

Improving the energy storage density

From the writer's trials and observations, greater energy storage (energy density) is possible for new design clock movements by using very high strength (2500 MPa) mainsprings manufactured by, for example, Haller-Jauch GmbH.

To realise their full potential, these springs need to be used in conjunction with larger diameter barrels (barrel diameter to mainspring height ratio up to 2.5:1), a smaller diameter arbor (down to 1/5 of the barrel diameter) and a spring thickness of 1/20 the arbor diameter. As an example, twelve currently-catalogued replacement Hermle mainsprings for use in their 8-day movements with strikework and chime-work have a mean $h.D^2$ value of 29,568 mm^3, which suggests a 28% improvement in energy storage density compared with the 41,156 mm^3 determined from the older clocks in my data set.

Reducing the energy demands of the movement

Not the subject of this paper, but from the writer's observations, energy demands are reduced by the use of ball bearings instead of plain pivots in brass/bronze bushes. Other measures include the use of lightweight, balanced hands and, of course, high quality workmanship. Low pendulum amplitudes also offer a significant reduction in pendulum air-drag losses.

Practical application

A given barrel geometry (useable volume) can only ever deliver a finite maximum energy, that delivered energy being dependent upon the yield strength of the mainspring (see earlier comments on fusee clocks and high-yield mainsprings). Consequently, the torque delivered to the movement must be traded off against the run-time (going period):

- If the delivered torque is too low, to avoid a fundamental re-design of the barrel geometry and gearing ratio between barrel and centre arbor, torque can only be increased by fitting a thicker mainspring and accepting a reduced (less than 8-day) run-time.
- If the delivered torque is too great (eg. excessive oscillator amplitude and/or banking occurs in the escapement), the delivered torque can be reduced by using a mainspring of reduced thickness and accepting a greater run-time (rarely a problem).

For these reasons, it is probably wise for the designer of a one-off clock to err on the side of a greater $h.D^2$ value in order to give a margin for torque adjustment during the trial period.

Summary

Starting from a requirement for a clock with a specific chapter ring diameter, I hope my exploration of a statistically-based methodology may offer an initial design point for the going barrel and its associated mainspring for a new construction clock.

Reference A: 'Clock mainsprings – a look at commercially supplied mainsprings', Guy Gibbons, *Horological Journal*, January 2020.

Annexe A. Curve fitting

Several curve fit functions were tried, the exponential fit being selected as best fitting the data while at the same time not suggesting a negative $h.D^2$ barrel volume at small chapter ring diameters. The perhaps easier to calculate linear curve fit function is more suspect in its underlying validity and would only be applicable over a limited data range:

Platform escapement: $h.D^2 \approx 340.CRD - 3000$
valid between 50 mm < CRD < 100 mm

Pendulum escapement: $h.D^2 \approx 200.CRD - 900$
valid between 100 mm < CRD < 200 mm

A comparison of the exponential ('exp') and (more pessimistic) linear predictions for 75 and 100 mm chapter ring diameters for platform escapement and pendulum clocks respectively is shown in Figure 4.

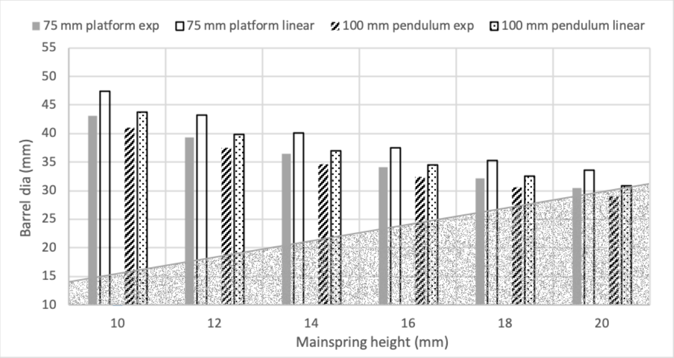

Figure 4: Comparison of exponential and linear predictions of barrel dimensions for selected Figure 3 clocks