BARREL-WOUND MAINSPRINGS

Part 3: Just how much energy needs to be stored?

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Introduction

Many devices require onboard energy storage, and so to a question: how does one determine how much energy needs to be stored in order to manufacture a successful product, be it a motor vehicle or clock?

Consider the purchase of a motor vehicle. How much petrol needs to be carried to deliver the performance and range that we require? It is a question that most buyers do not consider, and we assume that the manufacturer has sorted this out. Our choice of motor vehicle is almost entirely based on personal preferences (comfort, capacity, appearance, etc.) and (not least) prejudices associated with the marque. With a petrol vehicle, range is largely irrelevant as we assume the instant availability of a full 'recharge' at a petrol station taking around 5 minutes at any time of the day or night.

Figure 8: An early (2009) lithium-ion battery pack in a Nissan Leaf electric vehicle. At this time, the range was little better than 100 miles

But suppose we now wish to design a car? Where does the designer start? The science is certainly one starting point, as too is the engineering (can it be made?). But by far the greatest influence is meeting the purchaser's expectations, a point brought sharply into focus to those changing from a petrol to a battery electric vehicle (an "ev" or "bev") – Figure 8 – with their relatively low range, the limited availability of charging stations and their extended recharging time.

But let me set motor vehicles aside and turn to the subject of this article, viz. energy storage in a barrel-wound mainspring.

Energy storage

A mainspring is an energy storage and delivery device which, when wound in a barrel, is analogous to a rechargeable battery (secondary cell). Unfortunately mainsprings are very poor storage devices though perfectly acceptable for driving a clock for a reasonably convenient length of time, in many cases being better than that available in today's (early 21st Century) cell phones or portable computers (lap-tops or pads). A comparison of their volumetric ability to store energy – the energy storage density – can be seen in Table 1.

In comparison with other energy storage devices, mainsprings are not very good, Table 1 partly explaining why a clock powered by a single AA size alkaline battery having perhaps 1000 times the energy storage density will run for two or three years compared to a spring-driven clock that will run only for 8 days.

	MJ/litre
Uranium (nuclear fission)	1,500,000,000
Hydrogen (gaseous at atmospheric pressure)	0.01
Hydrogen (liquid)	10
Propane (LPG)	25
Petrol, diesel	35
Coal	40
TNT (explosive)	7.0
Battery, lithium-ion	2.0
Battery, alkaline	1.2
Battery, lead-acid	0.56
C21st reverse-wound watch mainspring	0.0025
Alloy steel – 1500 MPa yield	0.0015
Mild steel - 250 MPa yield	0.0005

Table 1: Some very approximate volumetric energy storage densities

At this stage we can now set science aside. The scientists have made their valuable contribution in developing the energy storage device, and the problem falls to the engineer to deliver the stored energy over a period of time that meets the expectation of the purchaser. Compared to a motor vehicle, this is (or should be) relatively easy for a clock (or watch) as it is a constant-power device that:

- does not depend upon the driving style of the owner,
- rotates at a constant speed, and
- is largely uninfluenced by the environmental conditions.

What it does depend upon is:

- the energy losses in driving the movement and escapement,
- the going period required of it, and
- the connected auxiliaries (watchmakers 'complications') such as calendar, strike and chime work.

In a motor vehicle, determining these demands is primarily undertaken by considering our experience of past successful designs. We all have a rough idea of the cubic capacity we require of a petrol engine (say less that one litre, one to two litres, or greater than two litres) but we really have no idea about much else associated with its selection.

And much the same can be said about clocks and, faced with a whole list of possible replacement mainsprings from our requisites suppliers, the question is 'where to start?' So, as a start, perhaps we can simplify the task by removing auxiliaries and going period from our consideration, the first by providing auxiliaries with a second or third energy storage device and associated gear train, and the second by assuming a going period of 8 days. This leaves the size (typically the clock's dial diameter) and, to a lesser extent, escapement type (pendulum or platform) as the primary determiner of the volume occupied by the energy storage device.

Energy demand

For all the many tens of papers on the theory of the spiral mainspring presented by scientists and mathematicians, none provides any guidance on the energy demand. To the practical engineer and clock designer, none is of any great use, so the writer undertook a statistical analysis on a small number of successful clock designs. All were 8-day mantel clocks, and the primary influencers selected were age (an approximate measure of the mainspring yield strength and (perhaps) quality of manufacture), and hd^2 as a parameter representing the volume of the barrel and hence energy storage volume[17]. Sample sizes were low: 18 with going barrels/platform escapements, 44 with going barrels/pendulum escapements, and 17 with fusee/pendulum escapements.

Yield strength

Taking all samples together, Figure 9 indicates how improvements in mainspring steels and perhaps manufacturing quality have improved the energy storage density. Goodness of the curve fit (the R^2 value) is poor, but it is perhaps a starting point to explain why high-yield steels (and the elimination of the fusee?) are beneficial in improving energy storage.

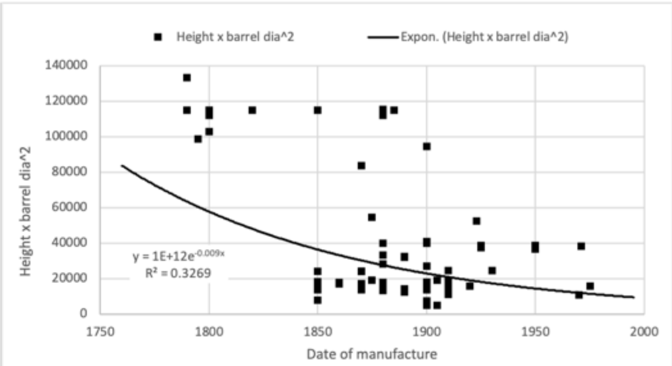

Figure 9: Indicating the increasingly compact mainsprings powering clocks of more recent manufacture. Example: an hd^2 value of 20,000 represents a barrel of around 35 mm inside diameter and mainspring of 16 mm height.

In the absence of yield and/or tensile strength data being supplied by horological requisites suppliers coupled with having no access to a tensile or hardness testing machine, the writer has had to resort to a very generalised estimate of the yield strength based on his experience of steels and the springback of observed springs – Annexe C. Table 2 gives the writer's interpretation in the improvement in yield strength over the years.

Steel	Typical period	Yield stress, σ_y
Carbon steel, annealed	C18th to early C19th steel	350 MPa
Ditto, quenched and tempered	Mid C19th to late C19th steel	1200 MPa
Alloy steel, quenched and tempered	C20th steel	1200 to 2000 MPa
Ditto, quenched and tempered	C21st steel	> 2000 MPa

Table 2: Estimated mainspring yield strength through the ages

Chapter ring diameter

Focussing on the clock to be designed, Figure 10 shows the same hd^2 parameter plotted against chapter ring diameter, the latter being a measure not only of turning an unbalanced pair of hands (and especially the energy demanded in raising of the minute hand in the second half of the hour) but also the generalisation that the larger the clock the more likely is the movement to demand greater energy.

Figure 10 suggests:

- fusee clocks with their low-yield mainsprings are energy inefficient, and would be more so if the volume occupied by the fusee and associated driving line were taken into account,
- platform escapements are more efficient for clocks with small diameter chapter rings (dials) but are quickly overtaken by pendulum escapements for chapter rings greater than around 75 mm diameter[18].

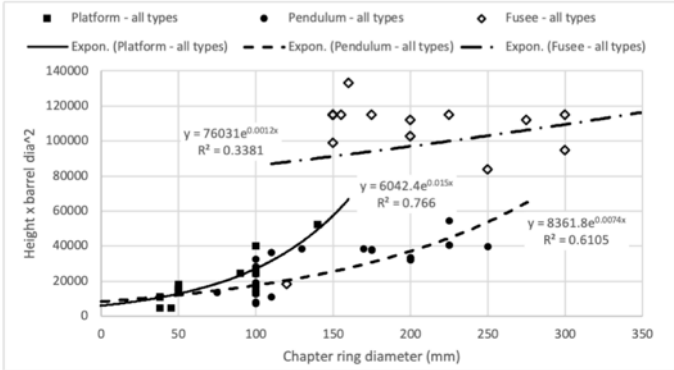

Figure 10: 8-day barrel size v. chapter ring diameter

The modern clock designer

From the writer's many years of study, modern high yield steel mainsprings ($\sigma_y \geq 2000$ MPa) and d/5 arbors are undoubtedly the most efficient way to go. Using these springs in a going barrel coupled with maximising the barrel diameter in preference to its height, my preliminary suggestion would be to aim for a mainspring hd^2 value in the region of 20,000 to 30,000 for a 100 mm chapter ring diameter mantel clock – Figure 11.

Figure 11: Two modern mainsprings, the preferential silver-coloured left-hand spring suggesting a higher yield steel hardened and tempered in an inert atmosphere

Summary – Part 3

Essentially, the writer's approach outlined above is design by statistical analysis rather than classical mathematics or trial and error. It is an approach that can only be embraced now that powerful tools such as Microsoft *Excel* have become available, and is something the forward-looking horologist would surely welcome.

I fully acknowledge that the above analysis not only lacks data but also requires a true leap of faith that the writer has embraced all the significant factors affecting energy consumption by the movement and escapement. Any comments would, therefore, be very welcome; indeed, maybe there is an opportunity for a wider survey of successful clocks compiled by clock repairers under the umbrella of their corporate association? See Annexe D.

As far as clock design is concerned, while there are indications that hd^2 gives an indication of the overall energy storage requirements, releasing that in a useful form for the movement requires quite a bit more analysis. Indeed, what we now want to know is the torque and number of turns delivered to the centre arbor, this being determined by the mainspring thickness and yield strength and, not least, the gearing ratio between mainspring and centre arbor. But all this is for another time.

An overall summary – Parts 1 to 3

Seemingly hugely neglected by the horological press, an understanding of the engineering – not science or mathematics – of clock (and watch?) mainsprings is a matter in sore need of attention. In contrast, the use of weights to drive a clock is child's play, though even here the necessary driving forced tends to be the result of little more than trial and error.

The writer freely admits his deliberations on mainsprings are very much work in progress, so comments would be most welcome.

Annexe C – Springback

There is an engineering science developed primarily for the sheet metal bending industry called springback, springback seeking to predict the amount by which a piece of metal springs back when bent beyond its yield stress[19].

Springback is essentially how a clock mainspring delivers power. On initial winding to its fully wound condition, the mainspring steel is taken beyond yield, and on unwinding it springs back to a far larger diameter, but not to the effectively infinite diameter of the straight strip from which it was originally coiled. It is this springback torque that drives the clock.

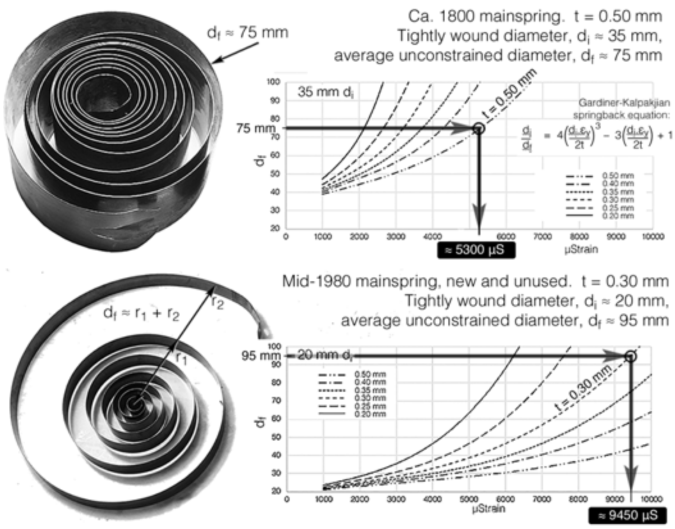

Figure 12: Estimation of yield strain of two mainsprings using springback theory

Swift[20] back in 1974 applied the standard sheet metal industry Gardiner-Kalpakjian equation to spiral mainsprings and, from his very limited investigations and analysis, the writer has found reasonably good correlation. The equation is included in Figure 12 where: d_i = diameter to which bent

d_f = diameter after springback

t = mainspring thickness

ε_y = yield strain of mainspring material[21]

The primary problem is that each coil is bent to a different initial diameter d_i (radius r_i), so if used to estimate yield strain, it is perhaps best to consider just the outer coil. The cubic Gardiner-Kalpakjian equation is cumbersome to solve for ε_y, so the writer produced charts for a range of mainspring thicknesses and fully wound (tightly-wrapped) diameters. To use the method requires three measurements:

- the spring thickness,
- the fully wound diameter, d_i (which can be estimated at around 2/3 of the barrel inside diameter on the assumption the barrel is reasonably optimally filled), and
- the relaxed diameter out of the barrel, d_f.

Figure 5 shows the writer's estimation of the yield strain for just two mainsprings and, as expected, it can clearly be seen that the springback of the lower Ca. 1980s spring is far greater than the upper Ca. 1800 spring. The charts to the right indicate how the estimated yield strains of 9,450 and 5,300 µS are estimated. But it is a cumbersome method, leaving one wishing that mainspring suppliers provided data to support their products.

Annexe D – a statistical database?

The writer has in mind a member-accessible database embraced within the association's web-site, the key requirement being to minimise the impact on the repairer's time (and hence cost) while still delivering meaningful data. An outline of the sort of format I have in mind is suggested in Table 3.

Description	Age (or σ_y)	Chapter ring dia.	Escap't	Spring height	Barrel ins. dia	Arbor dia	Other data
Hermle	1980	75 mm	Pend'm	12 mm	35 mm	7 mm	
French	1870	50 mm	Platform	19 mm	30 mm	10 mm	
Etc.							

Table 3: An outline for a data collection table

17. h = height (width) of the mainspring and d = barrel diameter. Mathematically, the volume of the barrel is given by volume ≈ $\pi hd^2/4$ or volume $\propto hd^2$. In practise, arbor diameter, barrel hooking and mainspring yield strength are also significant.

18. Much of the energy needed to drive the clock is absorbed by the oscillator air drag (pendulum or balance wheel). With spring-balances generally having a lower 'Q' (greater energy loss per cycle) than pendulums, maybe this is to be expected?

19. Clearly springback is useful for determining to what angle a sheet of metal needs to be bent so it, for example, bends back to 90° to form a flange for attaching side panels to, say, a washing machine casing.

20. *Influence of spring-back on the characteristics of the spiral spring*, WAC Swift, Proc IMechE, 1974. Springback was further explored by Emmerson in his paper Mainsprings in barrels, NAWCC Chapter 161, Horological Science, Issue 3, 2010.

21. Strain (ε_y) measured in microstrain (µStrain or µS) is preferred by the writer to stress as it is the release of (elastic) strain that drives the clock.
