DEVELOPMENT OF A NON-RESONANT EDDY CURRENT RATE LIMITED CLOCK MECHANISM

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INTRODUCTION

One is quick to assume that the art of mechanical timepieces has surely died out at the hand of the quartz resonator, its heyday long passed. Some of us are enjoying a resurgence in interest verging on a renaissance in mechanical watch innovations, and to a somewhat lesser degree, in clockmaking. For me, precision clockwork is the ultimate expression of mechanism.

Very recently, the world record was set for accuracy in a mechanical clock with a pendulum in free air, the amazing Burgess Clock "B".

Figure 1. The Martin Burgess "Clock B"

Clock B uses the physics developed by John "Longitude" Harrison in the 1700's, conclusions and methodology misunderstood and discounted by his contemporaries. His was a maverick effort of invention, tool creation and systematic correction that now understood, inspires a new generation of horologists.

Harrison, famously winning the £20,000 prize for a practical method of determining longitude at sea, was discounted by the experts of his day for claiming that he could build a pendulum clock with an accuracy of one second in 100 days, and would run for centuries without service, but he was mostly ignored because he was vocally cranky with his peers about their pervasive adherence to what he considered silly notions applied to precision clockwork. When he passed, still recognizing no equal in clockmaking, his technology sat idle for centuries until his physics and his unique language about it was deciphered by a group of professional and amateur horologists called the Harrison Research Group. This new understanding was then faithfully applied to create Clock B. The clock surpassed his claims by a wide margin, though with a slight nod to some modern materials, and, gasp, ball bearings.

Surely, I thought, no rock has been left unturned in all these centuries? That is largely true, with the most dedicated horological minds attempting to best each other for so long. Attempting to trod new ground has been at the same time highly rewarding, and profoundly frustrating. I literally am considering renaming the paper to: *"Why Would Anyone, in All of Space and Time, Attempt to Achieve Parts Per Ten Million Consistency in Any Basically Useless Machine?*"

This paper is not however about the rarefied air of high precision clockwork, but about a spinoff project that spawned from my desire for a smoothly running train for such a precision clock attempt, daring to equal Clock B with entirely and wildly other means. That effort of course may be futile.

I'd known about the odd behavior of a magnet slowly sliding down an aluminum plate due to eddy current damping for many years, and always wanted to use the effect for some fun purpose. My initial experiments with a rate limiter using eddy current damping showed promise as a timekeeper in and of itself, diverting me away from the *actual clock project,* which will attempt to break new ground in the pendulum, a much more crowded innovation space.

THE EDDY CURRENT CLOCK

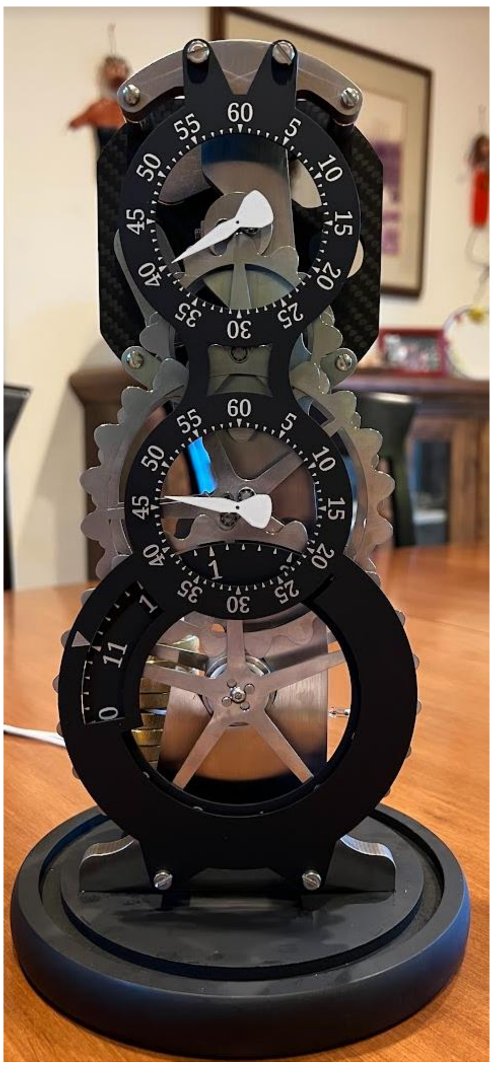

Figure 2. The clock with its glass dome removed

I began to wonder how far one could go toward precision with a non-resonant approach. Two examples of non-resonant timekeeping with extremely limited upper end would be water clocks and hourglasses. I find that for an experimenter like me, this subject goes quite as deep as one might want, and as with most difficult developments, fodder for an essay for another time: *Spinoffs Happen.* Sometimes very interesting spinoffs happen that divert you for years!

What I wanted to accomplish in this design:

- 100% rolling contact geartrain
- Smoothly sweeping hands
- Stainless steel construction
- Gravity power
- As little mechanism and hand work as possible
- A reasonably good-looking instrument
- Explore the upper limit of non-resonant, damping based timekeeping

The layout of the clock, *Figure 1*, is technically called a 3-wheel table clock. It has 4 arbors (axles), and three wheels. The 12-hour wheel rotates retrograde, and so it carries a dial so that hours are read with respect to a static pointer. The step-up ratios from bottom to top are 12:1, 10:1, and 6:1.

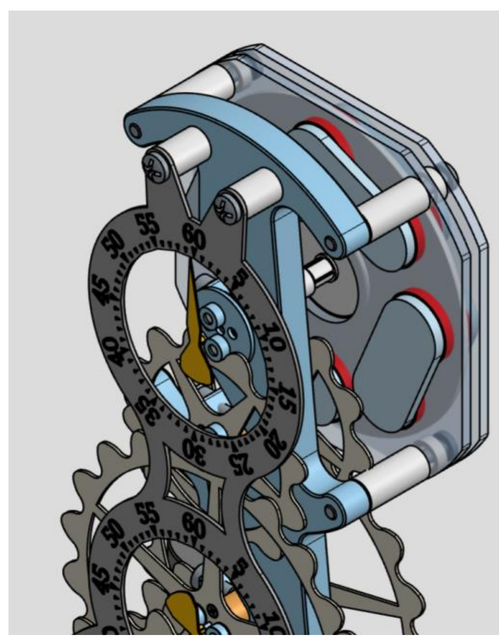

Figure 3. Magnets (red) with pole pieces to close magnetic circuits

Power in the form of torque goes in at the great wheel at the bottom and is damped at the seconds hand arbor at the top.

The damper itself is an aluminum hard drive disk attached to the seconds arbor, running through the magnetic field between 8 pole pairs of magnets, which live in two carbon fiber scaffolds sandwiching the disk with an air gap either side, Figure 3.

EDDY CURRENT DAMPING, BRIEFLY

Eddy currents are created in metals, when passing at right angles through magnetic field lines. This creates currents that circulate in the metal, that generate a magnetic field that opposes the metal's passage through the field. While ferromagnetic metals would work, reacting attraction force is something I'd rather not deal with on top of everything else. Aluminum, copper and silver are all better candidates for now. The main advantage is that it is a frictionless and smooth source of drag.

It has the same character as a paddlewheel in air might, that is, drag increases with the square of its velocity through the field, and so there is zero drag at zero velocity. Meaning, if the mechanism slows, then more torque is let through. Both devices have a dependence on the consistency of the torque applied: more torque, faster running. The earliest mechanical clocks, pre resonant element, had some form of friction as the rate limiter, with the attendant variability that friction brings. Some quite interesting regulation methods were used, but ultimately resonance was just able to take things to an entirely new level, minutes per year versus minutes per day.

THE WHEELS (We engineers say gears)

There is a fascinating book by W.O. Davis called "Gears for Small Mechanisms", which claims to be the definitive authority on involute vs. cycloidal tooth forms, and I have to say it's a good read, and I am not going to argue!

I, an involute gear-head, had to completely embrace the cycloidal tooth form after reading this book, mainly because it is ideal for roller pinions, but also because they are best for a back-driven geartrain, as this is.

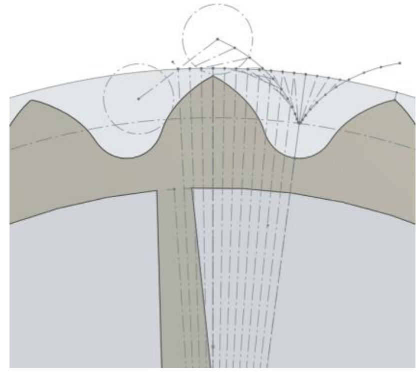

Figure 4 Step and rotate generation of cycloidal teeth with two rollers using Onshape cloud-based design software

Horologists call this a "going train", ultimately a 1:720 ratio from great wheel to the seconds hand.

If you've ever tried and failed to back drive an industrial gearhead of more than 100:1, you'll have an appreciation for the efficiency required of these three meshes, when the drive torque is on the order of 2 in-lb.

For expediency, the wheels were laser blanked and a rig made to grind the rather rough edge to smoothness. The tooth form was spread out 10%, and the tips reduced so that if you squint, it is reminiscent of a sinusoid. This conspires to make the gravity fed grinding rod roll over the profile easier. The cut depth is limited to something less than full cleanup, so that the geometry is not significantly changed from its (assumed to be quite accurate) laser cut profile.

Figure 5. Gravity fed tooth grinder

This approach works well with a bit of cutting oil. The 3000-grit ruby rod surprisingly did not load up in the process, rather the particulate was carried away quite nicely in the oil.

TWO TOOTH PINIONS

The recognized minimum number of rollers in a roller or “lantern” pinion is 6, arguably 5. I wondered what it would look like if the goal was 2. What it looks like is unusably unstable unless you have two wheels, one-half tooth out of phase, and the two sets of rollers on each face clocked 90 degrees. The benefit of two teeth per mesh is large teeth, which allow large rollers. The largest single reduction ratio is at the great wheel, which is 12:1. Two rollers on the pinion allowed me to have a wheel of something less than 6”. Any other pinion tooth count grows this size beyond what I would want in a table clock.

Figure 6. Wheel sets on their arbor bearing cartridges

The hybrid ceramic ball arbor bearings and rollers are of a ubiquitous size (.125” bore, .25” OD) intended for a dental drill handpiece. Read that as: *the smallest I could find, selected for lower cost due to mass production.* Ceramic balls are preferred so that this mechanism can run without lubrication that might change with time, primary of Harrison’s tenets, but not entirely necessary here. I wanted to explore and get experience with the techniques of running for centuries, but this one may not merit that chance.

The goal being that I want to stay entirely out of the condition of *stiction*, and so unlike a clock with an escapement which stops and starts the train every second or more, my train runs continuously, staying in the more consistent realm of dynamic and rolling friction.

Figure 7. One side of the two-tooth pinion

REWINDING

Generally, a clock will have some extra mechanism to provide maintaining power to the train while it is wound. This typically requires two ratchets and a spring loaded by the driver. This is true of drop-weight or spring power. Other methods abound, but I elected to use the same method as in Clock B, simply a mercury level switch and a gearmotor with a worm drive set on the great wheel arbor. The brass weight falls through a small angle, the mercury switch engages 4.5vdc to the motor, driving the weight up slowly, resetting it to fall again. This occurs every 20 minutes or so. The main advantage is that this simple approach keeps torque constant enough throughout the process.

Figure 8. Worm drive rewinder

Some horologists might call this an *electric clock* since it rewinds using a DC motor, but perhaps it is more of a *magnetic clock*.

WHAT A CLOCK IS

Horologists and amateur horologists like me are fond of the following observation: A clock is a mechanism designed to keep time. Once it is keeping good time, it usually then becomes a very sensitive thermometer, which the plots below will attest to the change in rate due to temperature. In a pendulum clock, once you have correction for temperature, then the buoyancy of the pendulum bob becomes a sensitive barometer, and once you've corrected for that, your concern turns to air density, and so on, and if extremely high fidelity, ending with fluctuations in gravity which are arguably uncorrectable. My clock mechanism is concerned only about temperature and consistency of power input, and I don't dare dream of the need to adjust for barometric pressure, where the driving weight becomes more buoyant with pressure. It is unlikely the fidelity will get there, and so higher order effects are lost in the noise.

TESTING

One of the early breadboards pointed out that there was a large sensitivity to temperature, and no clear explanation pointing to thermal expansion of materials. A deeper dive was required, quickly and unexpectedly pointing to a culprit: changing magnetic field strength. I had no experience with the thermal coefficients of magnetic materials, which were startlingly present and unaccounted for! In a full treatment, one must also consider the change in resistance of the aluminum disk with temperature. Both conspire to speed up the mechanism as temperature goes up; the eddy current damping having been reduced. I now expect that further work will need a professional take on the magnetic circuit in detail, disk alloy, scaffold, air gaps and all. AlNiCo and Samarium Cobalt (SmCo) magnets can be formulated to have a slightly negative thermal coefficient to account for the positives in the rest of the path.

Rate tests were performed using a MicroSet Clock Timer, with an optical sensor positioned to be broken with the seconds hand. Three types of readily available magnet materials were considered, Rare Earth NdFeB disks ("Neo's"), hobby grade ceramic disks, and AlNiCo 5, which was predicted to be the most stable. In the following charts, the left axis is rate in seconds (blue), and the right is temperature (red).

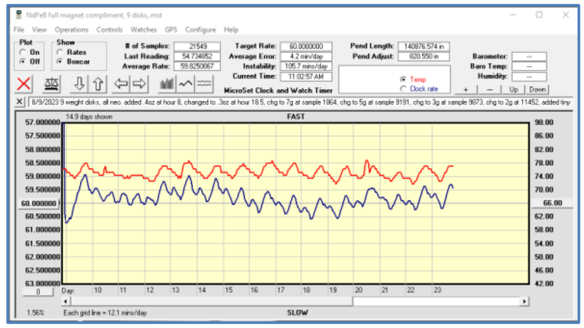

Figure 9 NdFeB full complement (plotted using the Microset precision clock timing interface software)

The rare earth magnets had the strongest field, and so required the largest driving weight. I mention this because it is known that the more energy I burn driving this train, the more consistent it will be, if friction is minimal. I like to look at it as this: the lighter the drive weight, the less able the mechanism is to bull its way through little irregularities.

There are deeper waters there that harken to Harrison's quite correct philosophy he called the resonator's "dominion" over the motion work, and so he had far greater swings to his pendulums for more stored energy. It is one of the main design goals, to have high as practical drag and high driving weight for the best results. For now, it should just temper our conclusions from these plots, as the drive energies are greatly different.

Temperature dependency of the Neo's is on the order of 0.09s/min/deg, or a rate sensitivity of 0.14% per degree. The ceramic magnets came in at more than twice this, at 0.21s/min/deg.

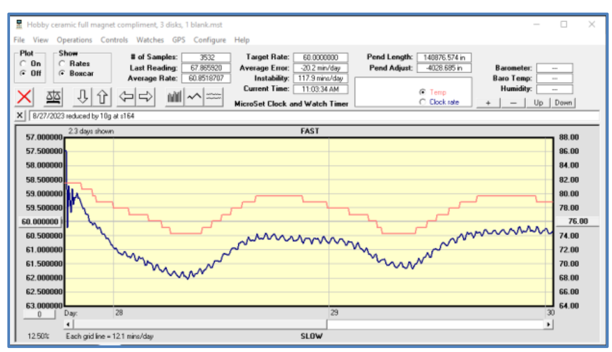

Figure 10 Hobby Ceramic full complement

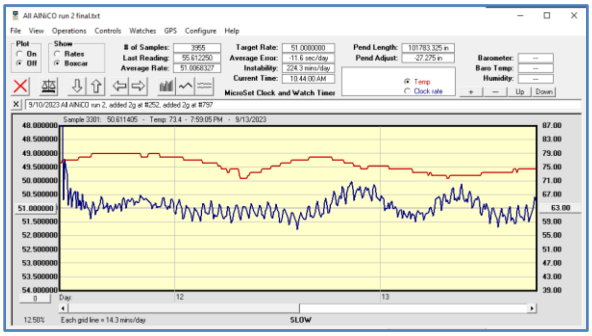

Figure 11 AlNiCO full complement

The ceramic magnets operate at about 1/3 of the driving weight of the Neo's. As of this writing, shown is only the first few days of data from the AlNiCo 5 magnets, and as expected, the temperature sensitivity is greatly improved, in fact, it is encouragingly difficult to see a correlation. However, the field strength is very much less, and so the driving weight is one quarter as much as needed for a full complement of the Neo's, so the results are masked a bit by the sensitivity to drive weight, but the trend is clear and per theory.

FURTHER WORK

I would like to continue to explore non-resonant timekeeping to see how far it can go. The short-term rate fluctuation of this mechanism would benefit from a mechanical feedback device and dynamic adjustment of input torque, which is a tremendously interesting rabbit hole to inhabit for a while.

If I can make this timekeeper to be accurate to two minutes over a period of 20 days or so, I would consider taking it on a transatlantic ship ride to see if it would have been remotely possible to win the £20,000 Longitude prize of the 1700's, with something entirely other than John Harrison's incredible H4 balance wheel regulated marine chronometer. Though to be true to the skill and materials of the time, I'd need to use jeweled bearings and lode-stones for magnets.

Acknowledgements

Many thanks to my friends in the horological science community, too many to list. Their incredibly valuable critique of my regular ravings, and help with interpretation of data I've gathered, grounds me and shortens the development process, if my ears are open. To Bryan Mumford of Mumford Microsystems, maker of the MicroSet Precision Clock and Watch Timer used in this work, as well as neighbor and friend.

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