# Another Approach for Precision Electronic Pendulum Management
## By Jim Hansen

My experience as a clockologist began about six years ago after retirement as an embedded systems engineer when I was introduced to Huygens 1658 article “Horologium” that described his famous clock with the cycloidal cheeks. Surely, thought I, such a clock would be easy to make, given the primitive tools of that time. (I was wrong.) Later I went through my “Harrison” phase, all the while assembling a reasonably small workshop and building a Synchronome from scratch. My interest in the free pendulum began in earnest about three years ago.

A couple years ago a friend loaned me a cache of HSN back issues and I began reading the stories of discovery reported within those pages. I've pondered the subject for some time and have a few thoughts that may be used as a new approach for precision pendulum design, excitation and readout that perhaps haven't been described in these pages. As the test system for exploration of these principles is starting to take shape, comments and discussion from this learned and experienced readership is welcomed.

Horological Pendulum Servo Systems

Most recently described digital electronic pendulum excitation systems are based on the so-called “bang-bang” servo, a primitive on-off system originally developed for use with relay logic in early missile guidance systems, and informal origins long before. As applied to pendulum control, this approach maintains pendulum swing amplitude by delivery of a fixed “quanta” of energy to the pendulum whenever the swing amplitude is too low. Once boosted, the pendulum coasts until another impulse is required. Other systems deliver small impulses on each pendulum swing (mimicking mechanical clocks), and analog systems that use the pendulum as a resonator.

By its nature the bang-bang servo is not supremely accurate because the impulses supplied by it are of uniform value and cannot precisely regulate the pendulum swing amplitude. Indeed, it boosts the pendulum some unknown distance past the amplitude sensor, then lies in wait as the pendulum coasts down and no longer reaches the amplitude sensor. This is the electronic equivalent of the 19$^{th}$ century Hipp toggle, although with much improved reliability.

Such systems make an apparently mistaken assumption that if the swing amplitude is precisely maintained, then nature will make sure that the pendulum takes the same time to fall through its arc on each and every swing. In practice this is somewhat less than always true for several reasons.

Although the bang-bang servo system is simple to implement, it does not correct amplitude errors precisely or as soon as detected. Bang-bang systems so far described monitor pendulum swing amplitude only on swings in a given direction. Its first notice of a low amplitude condition takes place *after the pendulum returns from the altitude sensor proximity and travels past the bottom of dead center (bdc)*, about a half a second after this deficiency could have been noted and corrected. It then takes about another second before the pendulum, passing the bdc on its return flight, is given the correcting impulse.

Another fundamental shortcoming of the bang-bang system is that it provides only monotonic impulses, meaning that they are of a single energetic value and are not modulated according to the error amplitude. This results in either driving the pendulum well past the amplitude sensor, thus requiring a variable coast-down period in some cases exceeding a minute, or possibly not driving it hard enough to reach the sensor causing another immediate impulse to be issued. Variability in freely swinging pendulums at low amplitudes is well known, and given the bang-bang system cannot immediately and accurately correct amplitude errors suggests that another approach might be of interest.

## A Modest Proposal: A Pendulum Servo System Based on Pendulum Velocity

A more sophisticated servo system, one based on maintaining pendulum velocity rather than amplitude, has a number of advantages. If the actual stored pendulum energy is monitored, then immediately corrected during each swing, many of nature's variables influencing pendulum performance *might* be minimized.

Unlike pendulum amplitude, velocity is easily sensed by use of an inexpensive optical interrupter and a slitted flag mounted on the pendulum. Such techniques have been previously described in these pages. (1) As the pendulum (kinetic) energy reaches a maximum at the bdc of each swing, and the swings are symmetrical about the bdc, this is the most ideal location for taking pendulum measurements.

Pendulum energy is proportional to the square of the velocity, and so monitoring pendulum speed and comparing it on a pass-by-pass basis will reveal the energy lost on each swing. (2)

Given that pendulum speed is measured on two consecutive passes, Q can be found by:

$$Q = (2\pi/t_n^2)/((1/t_n^2) - 1(t_{n+1}^2)) \quad (3)$$

Finally, the actual pendulum rate *can* be measured from slit-to-slit timing using the same slit gathering velocity data, but this presents several difficulties that will be shortly described.

Because most pendulum metrics can be mathematically derived from velocity, there is little need for more complex instrumentation. Although pendulum speed can be measured in a single pass, such a measurement is only representative of the the speed at that moment. Depending on the quality of the pendulum mechanism and the atmospherics at any given time, each pass will exhibit variations in both arrival time and velocity. Such “noise” is usually averaged out or passed through a low-pass filter.

Once pendulum velocity has been sensed it is fed to a controller, whose function it is to maintain the velocity at some pre-established level. Probably the most common such control system is called a “PID” controller. These initials stand for Proportional, Integral and Differential, and is a system developed in the 1940s that was (and is) quite successful when implemented with analog electronics. Its advantages are that it can maintain tighter control over a variable process, for example, motor speed control or building heat, than simple on-off (bang-bang) systems.

All controllers are given a target speed or whatever that they are to achieve and maintain, such as the “setting” of a thermostat. In our case, we want the pendulum slit timing to be a constant number so our “setting” will be called the “slit reference,” the value the controller will try to maintain.

PID controllers combine three control methodologies. Proportional control works by providing less and less drive power to a system as it approaches nominal speed, thus it rarely actually reaches its goal or target speed. The integral function takes a look at the history of speed correction and generates a value based on a historical average; the differential function looks at the very latest difference between the slit reference number and current speed. These processes are "tuned" by combining their outputs in different proportions. Every application requires individual tuning; it isn't a "one size fits all" type of thing at all.

Once the controller variables are tuned for best performance, the output drive, in our case a pendulum magnetic drive, is adjusted so that during a nominal pendulum pass the slit sensor reading will read the same as the slit reference time.

Pendulum performance metrics are calculated on each pendulum swing and are available as "errors". Also available is the record of the amount of energy the controller injected into the pendulum to correct those errors. In my version of this controller, all data will be sent to an ancient but adequate laptop for storage and analysis.

It is not difficult to implement nor expensive to develop a PID control system using a Microchip PIC processor. (4) The PIC 18F24k22 processor at about $3, for example, has more than enough processing power to implement a sophisticated and robust controller. A precision crystal oscillator for absolute pendulum timing costs a little more, around $3. Crystal oscillators at this price have a questionable extended long-term rate, but can always be replaced with a more precise standard if required. Little additional controller electronics is required. With prudent shopping the total parts cost will be under $20.

A block diagram of this controller is shown in Appendix I.

Firmware for such a controller, which does go a little beyond trivial, is not difficult to develop as most functions will turn out to be modular in nature. These are easily written and debugged on a piecemeal basis. Microchip provides a powerful and free debugger-simulator as well as a free C compiler. An assembler is also available for free, but with careful design, little if any assembly code will be needed.

The controller for this project is more complex than necessary for a "real" clock because of its research nature. For example, it has a two-line display for parameter display and setting. A pot connected to one of the A/D converters on the processor chip is used to "select" the parameter which is displayed on the top line, and a second pot selects the parameter value to be set as shown in the lower line of the display. A push button switch then "sets" the value. This is obviously not useful in a normal clock installation.

A multitude of variables are programmable using the same panel. For example, the pendulum impulse value currently in use can be read out and changed; the desired pendulum velocity is another. Some variables are "read only" such as current pendulum velocity, or timing. In general, most pendulum data is sent serially to a computer for storage and analysis each second.

Of special interest are the control "modes" that can be used. These include bang-bang (a second optical interrupter must be provided and appropriately positioned for bang-bang operation), continuous (similar to a common mechanical movements), PID and others that might show up. Front panel switches allow control of each of the three PID elements to be turned off, convenient when tuning for a given pendulum.

Because multiple controlling methodologies are provided, study of fundamental pendulum behaviors is easily possible. Conversely, a given pendulum can easily be studied under tightly controlled conditions.

A Few Design Preliminaries

The "slit reference" number mentioned earlier is the pendulum slit timing measurement that the controller is to maintain. Although arbitrary, this number isn't mindlessly chosen. It is based on the approximate count that could reasonably be expected for the pendulum under test and is based on the expected bdc pendulum speed multiplied by the slit width.

For example, if we'd like our seconds pendulum to swing 1" (.5" each side of center) and we're using a .020" slit, our expected pendulum speed is a simple sine function, and the swing time, viewed through the slit, will be:

T = Pendulum amplitude (sin (π * slit width))
T = (sin (3.1416 * .020))
T = .00219 seconds, or a touch over 2 ms.

A 1 mHz clock will be used for our timer, and on a perfect pass the expected count is 2190. This is the value given our reference number. If we'd like to study pendulum performance with a wider or narrower swing amplitude, it is only necessary to change this reference number and a new amplitude will be automatically established by the controller when using it as a PID controller.

It will take the controller something under 100 μsec to calculate and start outputting the compensating impulse. Thus, in less than 3 msecs, pendulum error will be measured and corrected, all within .030" of bdc. It should be noted that error correction such as this must probably be done on *averaged* readings, not single passes, although the integrating function of the PID controller may take care of that.

Pendulum Impulsing Philosophy

Pendulum impulsing should disturb the pendulum as little as possible. A common discussion centers on whether it is better to issue one large impulse less often, letting the pendulum "coast" between impulses, or if the better choice is to impulse the pendulum more frequently with smaller impulses.

But if I may wave my arms a little, provided "pendulum disturbance" is measured as the ratio of impulse (or other disturbing) energy to the pendulum energy, it is obvious that the disturbance is lower for smaller impulses. If a pendulum receives an impulse that makes it coast for a minute before the next impulse is required, it represents a much "larger" disturbance. I've seen nothing in the literature to indicate whether pendulum "disturbances" are accumulative, nor has there been much discussion (that I've seen) indicating what timing errors these disturbances actually cause.

The controller being described is intended for research and so it will have the ability to operate with these and a variety of other impulsing protocols, allowing for the first time an "apples & apples" comparison study of this question.

Known Design Issues

There are several obvious pitfalls in such a system. There is the obvious question about the clock used to make measurements. Controllers can use absolute or ratiometric terms in their functioning. If we measure pendulum energy in absolute terms, for instance, we have to know the mass of the pendulum and actual speed, then do a calculation. Ratiometrically, we know *that the energy varies with the speed squared* and use the measured speed (or speed squared) as the energy figure in later calculations.

When designing ratiometric systems, terms common to both sides of a calculation or process, disappear. In this case, the controller clock is used for both pendulum measurement and impulse timing. Thus it is a common factor and absolute clock accuracy is not required over the long term. In essence all this clock does is define the pendulum slit and output impulse timing resolution.

This is not the case when an absolute value, such as pendulum swing time, is to be measured. Of course the alternative to all this controller complexity is to simply provide a fixed impulse on a regular basis as has been done for hundreds of years in countless clocks and watches.

Pendulum Magnetic Drives

Temperature sensitivity is a trait common to all magnetically-driven mechanisms and unless the output drive system is temperature compensated, the physical impulse imparted to the pendulum will have a negative temperature coefficient.

Conventional neodymium magnets, with their -.11%-plus per °C temperature coefficient are not desirable for use in a laboratory-grade impulse drive system. For that Alnico magnets (.013% - .007% per °C, depending on grade) appear to be much better suited. (6, 7)

On a practical basis magnets targeted for precise horological drive systems must ultimately be characterized and their temperature coefficients individually tested. Although a painful process, the objective is to establish an impulse drive temperature correction factor worthy of the next order of magnitude in pendulum performance.

When ultimate, long term accuracy becomes the goal, the magnetic detail cannot be ignored, regardless of the control system employed. The ratiometric system being described is completely blind to variations that affect the actual pendulum driving force. When the impulse applied to the pendulum is externally changed by whatever means, such as a tempco variation, the controller *assumes* the change was caused by a pendulum aberration or abnormality and “corrects” it without comment.

The Pendulum

The whole point of developing the above pendulum controller is for me to use it to develop an accurate pendulum. And so a few words about my pendulum project are probably in order. It has long been observed that a freely swinging pendulum swings only for so long before stopping. Classical observation blames “friction” as the culprit, and without further analysis we can say for certain that friction caused by the pendulum “rubbing” against the air and by suspension operation are the two main suspects.

As a comment this understanding is not complete. Vagaries, after 500 years of clock making research, still seem to exist. Perhaps the ether or dark matter are ultimately real and affect our art and science in sneaky ways.

My pendulum design is a seconds pendulum, quartz rod and when I can find it, a glass or quartz bob. Aside from the tempco of quartz being close to zero, the reasons for quartz and glass is that I want no electrical conductors in the pendulum mechanism. These prevent any current or magnetic field influence.

The quartz rod isn't a rod, rather, it is a 3/8" tube, and as testing progresses, it may get thinner. Bob Matthys reported that more slender pendulum rods tended to slightly raise Q (5)  I suspect this is an air friction-related issue and wonder if there would be a difference when the pendulum is in a vacuum.

Suspension systems have been refined over the years, with the knife edge and single point pivots probably providing the lowest friction and hysteresis. Other low friction systems exist, such as air pivots and levitating magnetic bearings, although I've not heard of their actual horological use. My suspension starts with a sapphire plate supporting a knife edge that may eventually evolve into a point or ball a few thousandths of an inch in diameter.

A fully informed atmospheric model is a minefield of interactive variables. My pendulum is going to hide from them all in a vacuum as soon as the drive system has proven reliable.

Summation

A high performance ratiometric pendulum controller supporting several pendulum excitation methodologies is under construction. Its purpose is to allow easy exploration and characterization of various pendulum designs and impulse philosophies. The basic controller amounts to little more than a PIC microprocessor chip, a photo-interrupter, drive coils and the power supply.

References:

1 *Electronic Measurement of the Amplitude of Swing of a Clock Pendulum HSN 2009-2*

2 *Measuring Q Based on Time* HSN 2007-4 p29

3 *Q Calculation from Time at BDC of a Pendulum,* HSN 2007-4

4 *Implementing a PID Controller Using a PIC18 MCU* Microchip AN937

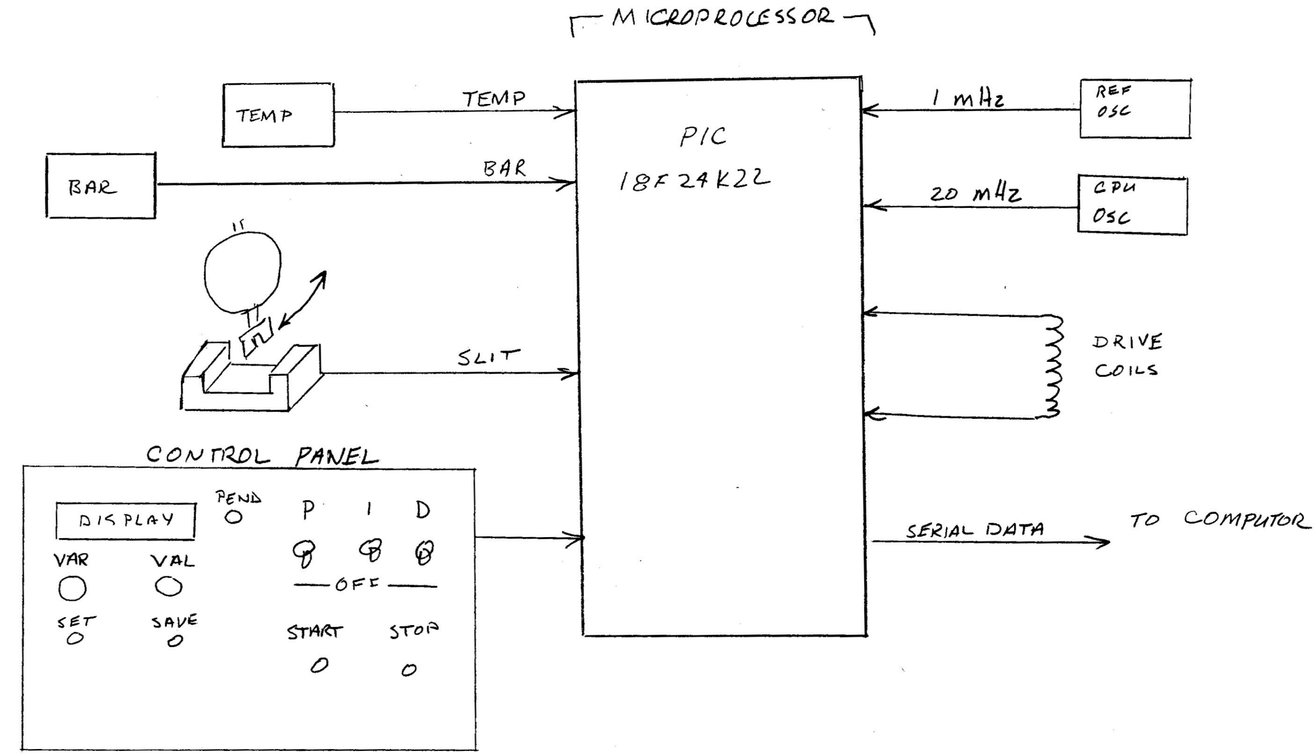
5 *Effect of the Pendulum Rod on Q*, HSN 1998-4 p7

6 *Permanent Magnetic Materials* MMPA Standard 0100-00

7 *Integrated Magnetics Data Sheet* http://www.intemag.com/magnetic_properties.html#Alnico_-_Magnetic_Properties_

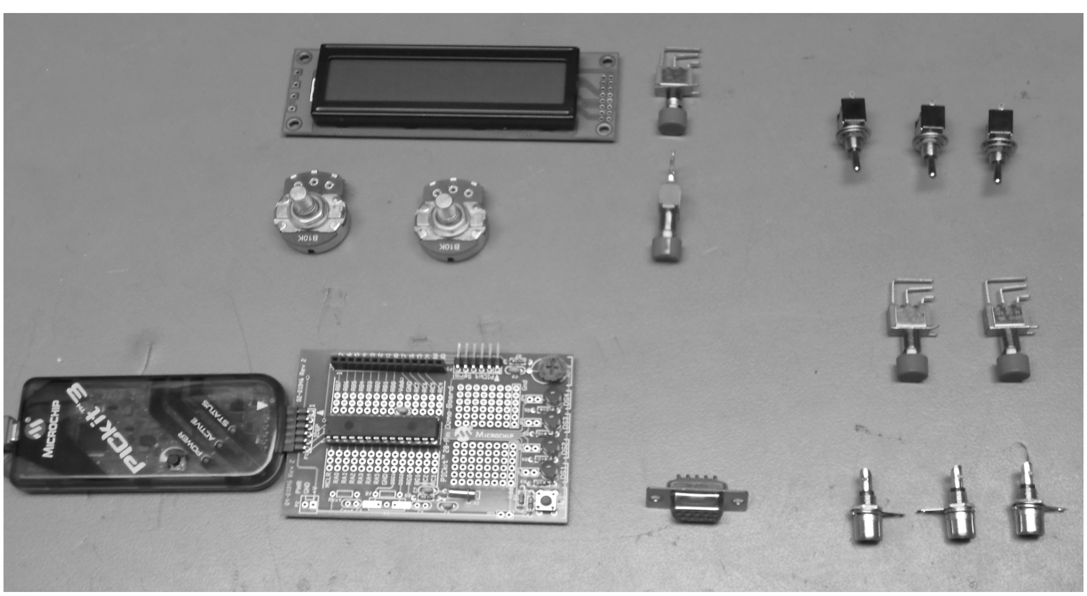
Appendix I

Block diagram of the controller. Most of the components are wired directly to the microprocessor.

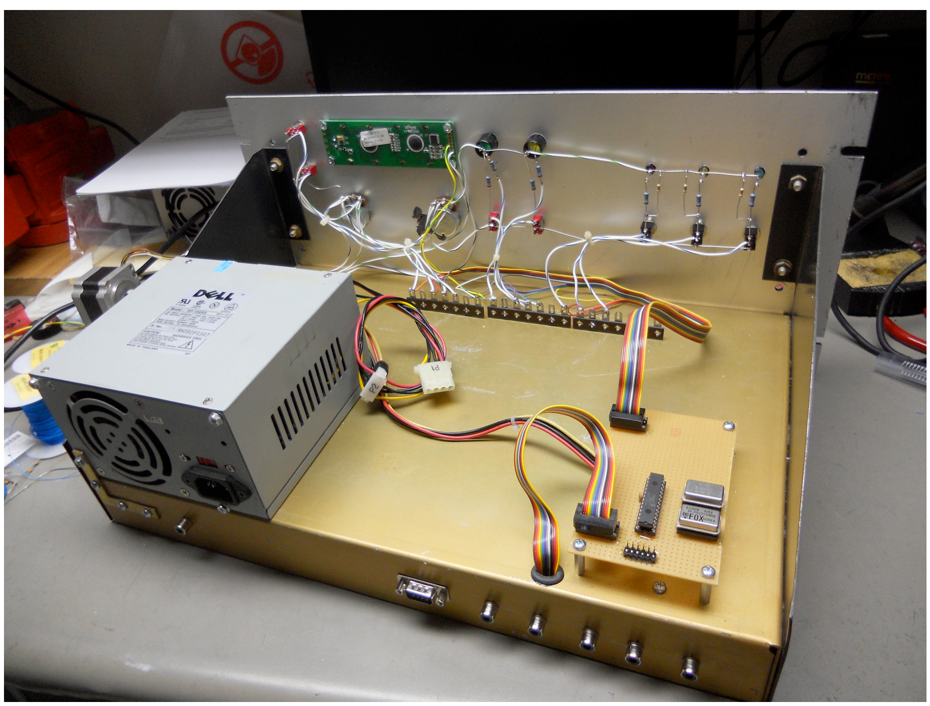



Appendix II
Parts Layout of controller. The major parts are shown. The PICDemo board, at bottom left, provides an easy way to wire all of the components in a prototyping way, and also lets the simulator-debugger run the program and "see" all the switches and other goodies during program development via the PICkit 3 programmer.

Shown in the upper left is the lcd display. Phono jacks at bottom right provide power to the pendulum drive coils and photo-interrupter inputs. Not shown are led indicators and additional connectors/switches. The controller will run from +5V, but when stripped down to a real clock application, it can run from a 3V battery source.



Controller front view. The rack panel and chassis used for the controller is much oversize, but in my case, cheap. The LCD display (upper right) will allow for easy, real time variable adjustment and readout. The two pots (no knobs) under the display are read with the on-chip a/d converter, allowing data selection and programming values. The large LEDs in the center blink to show the pendulum passing bottom of dead center and the amplitude sensor. These are mostly for fun and to give a sense that there is something going on.



Controller back view. The wiring in this controller connects switches and lights to the microprocessor which is mounted on the perf board, bottom right. Connections to the pendulum is made via the phono jacks across the back apron. Inexpensive multi-media cables are used to complete the connections.