A Simple Regulator

with an Isochronous Combination of Pendulum and Escapement

by Bernard Tekippe (GA)

Introduction

In the seventeenth and eighteenth centuries, great improvements were made in the timekeeping of clocks by fitting them with pendulums and temperature compensating these pendulums. However, two small variations, both related to the variation in the amplitude of pendulum swings, still continued to plague clockmakers. The first, circular error, is simply a characteristic of any pendulum that if it swings farther, it swings a little slower. The second, escapement error, is a variation in the speed of the pendulum caused by the clock driving it, which also varies as the swing of the pendulum increases or decreases. Many attempts have been made to keep the pendulum swing constant or to minimize the effects of changing pendulum amplitude, but with limited success. Now a new tool, the electronic clock timer, can measure the time of a single pendulum swing to a millionth of a second or analyze the pendulum rate over a period of time and graph it on the computer monitor. Small variations in circular and escapement errors can be measured directly and displayed as they occur. The experimenter can see the result of a change very quickly and before other factors influence the experiment. This instrumentation makes it possible to design an escapement whose change in escapement error tends to cancel the change in the circular error when the pendulum swing varies and to experiment with the escapement until this is achieved. As a result, the negative effect of these two variations is greatly reduced, and the pendulum speed changes very little when its amplitude changes. This ability to time the pendulum, along with a better understanding of escapement error in recent years, has made it possible to design a clock whose rate varies less than any other pendulum clock, except those in barometric chambers. This article explains the design of such a clock, which will be called a Simple Regulator.

Development of Precision Regulators

For as long as there have been clockmakers, there have been regulators. They were simply the best timekeepers the clockmaker could make or buy to time the other clocks that came into his care. In 1890, the typical regulator had a deadbeat escapement, driven by a four-wheel gear train with high-numbered pinions. It was wound once a week and had maintaining power to keep it operating while being wound. Often the escape and verge pivots and the pallets were jeweled, and the pendulum was temperature compensated. The dial usually had a center minute hand and separate circles for seconds and hours. It would have had a daily variation of about one tenth of a second.

Sigmund Riefler, a German clockmaker, set out to improve on this type of regulator; with diligent experimentation he developed pendulums with much smaller reaction to changes in temperature. At first, these were mercury compensated, but after 1897 he used invar, a nickel steel alloy with a small coefficient of thermal expansion. He also developed his own escapement to drive the pendulum by flexing the pendulum spring. It used two escape wheels: one for locking the gear train and one to impulse the pendulum. The escape wheel and verge pivots were jeweled, and the plates on which the pendulum spring rocked were agate. His greatest departure from the typical regulator was to put the entire clock in a vacuum chamber and maintain a constant pressure with a pump. This protected the clock from changes in barometric pressure. The clock was fitted with an electric winding system that wound it every 30 seconds, which eliminated most of the gear train and any variation in drive from this source.

Riefler's clocks were expected to perform as soon as they were installed, and he guaranteed their daily variation. He insisted on great care in their installation and would perform this service whenever possible. As a result, between 1900 and 1950, about half the regulators in the major observatories of the world were Reifler clocks. He sold several models of his clock. The model A was his best clock with his best pendulum in a dustproof wall case. Reifler guaranteed it to keep time with a variation between 0.03 and 0.06 seconds per day—much better than the standard regulator, because of his carefully made pendulum and escapement. The model D was essentially the same clock enclosed in a vacuum chamber, which he guaranteed would vary between 0.01 and 0.03 seconds per day.[1] These results show that his pendulum and escapement improved the timekeeping by about a factor of 3, and the vacuum chamber by about the same amount again. By 1900, with ten years of experimentation, he had reduced the daily variation of these clocks to 0.01 second, about one tenth of the 0.1 second variation of the typical nineteenth-century regulator.

To time his clocks, Riefler used star sightings to establish the time, which he compared to the time indicated on his clock. The accuracy of these sightings was about 0.01 second, but they could only be done on nights when the stars were visible. Clockmakers today are at a great advantage because timers give time assessments of this accuracy every second. In Table 1, we see the record of the model D Riefler clock No. 56 at the Case Western Reserve Observatory in Cleveland, OH, for three months in 1901 and 1902.[2] The purpose of the table is to calculate an average daily variation for the clock to permit comparison to other precision clocks. The first and second columns give the date and the error of the clock on that date. The third column gives the daily rate calculated by dividing the error since the last reading by the number of days elapsed. The daily rates are averaged to give a mean daily rate. This is the average amount the clock gained each day and the amount the pendulum would have to be adjusted to be right on time. The last column, the mean daily rate minus the daily rate, gives the daily variation from the average daily rate. The average of these deviations, ±.015 seconds per day, indicates the stability of the clock and is the figure used to compare with other clocks. It is the average daily deviation from the average daily rate.

Date 1901-2	Clock Error	Daily Rate	Mean Daily Rate Minus Daily Rate
Dec. 17	- 13.58s		
20	- 13.29s	+0.097s	0.019s
21	- 13.18s	.112s	.004s
Jan. 17	- 10.63s	.094s	.022s
19	- 10.41s	.103s	.013s
25	- 9.62s	.134s	.018s
27	- 9.42s	.100s	.016s
28	- 9.31s	.100s	.016s
20	- 9.09s	.114s	.002s
Feb. 4	- 8.41s	.135s	.019s
10	- 7.59s	.135s	.019s
15	- 6.89s	.137s	.021s
Mar. 5	- 4.60s	.127s	.011s
10	- 4.02s	.117s	.001s
13	- 3.61s	.137s	.021s
19	- 3.02s	.098s	.018s
	Mean Daily Rate	+0.116s	
		Mean	±0 .015s
		Max	0 .022s

Table 1. The average daily variation of Reifler's Model D No.56 is ±0.015 seconds per day.

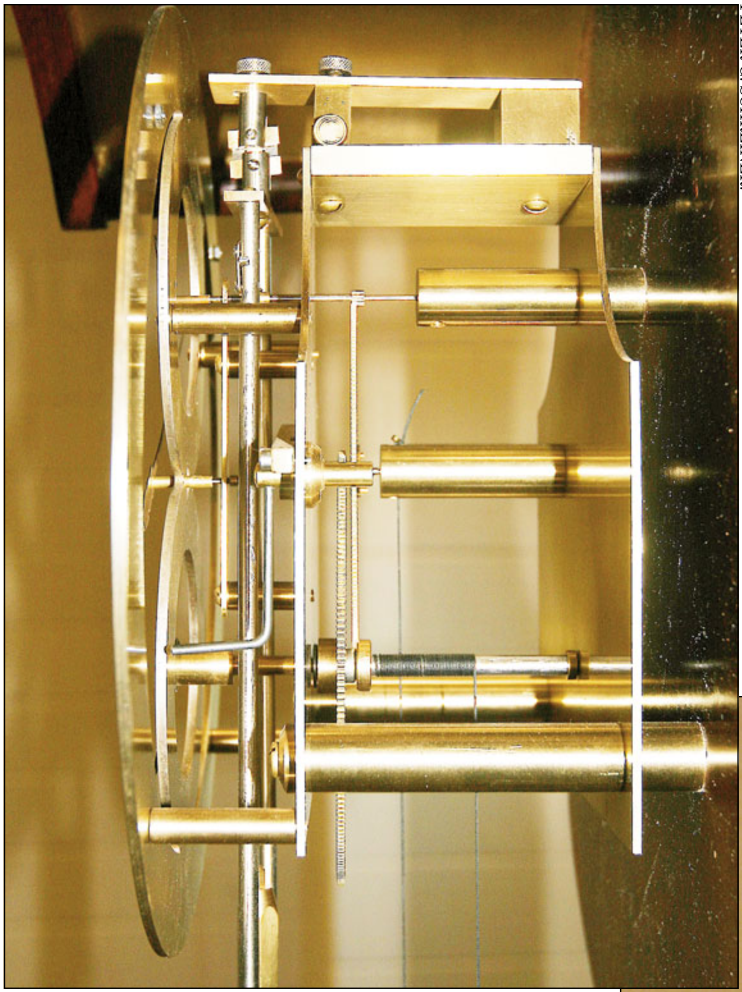
Development of a New Simple Regulator

My own clockmaking experience began in 1981 when a group of 12 NAWCC Atlanta Chapter 24 members gathered in my shop to build copies of one of Simon Willard's lighthouse clocks. We built cases and movements for each member of the group. The next clock was our first regulator, similar to the standard regulator of the 1890 period. Eight more classes followed over a period of 14 years, each resulting in changes and improvements that stressed simplicity of design and construction. Four members of the group attended the 1992 NAWCC seminar in Cleveland on Precision Timekeeping, which gave us many new ideas. We referred constantly to *The Science of Clocks and Watches* by A. L. Rawlings, which was first published in 1944.[3] We were delighted when a new edition was published in England in 1993 with new material added by nine contributors.[4] We invited two of the contributors, Douglas A. Bateman and Philip M. Woodward, to speak at the National Convention in Atlanta in 1997. All of these activities influenced the new regulator design presented here.

Week	Clock Error	Daily Rate	Daily Rate Minus Average Daily Rate
0	0.000s		
1	.138s	+0 .020s	0 .009s
2	.276s	.020s	.009s
3	.397s	.012s	.001s
4	.561s	.023s	.012s
5	.708s	.020s	.009s
6	.786s	.011s	.000s
7	.898s	.016s	.005s
8	.925s	.003s	.008s
9	.925s	.000s	.011s
10	.925s	.000s	.011s
11	.951s	.003s	.008s
12	.960s	.001s	.010s
	Mean Daily Rate	+0 .011s	
		Mean	0 .008s
		Max	0.012

Table 2. The average daily variation of the Simple Regulator is ±0.008 seconds per day.

The Simple Regulator was also developed from the standard regulator. Changes were made in the gear train and a carefully adjusted invar pendulum was used. The most important improvement was the change in the escapement designed to deal with changes in circular error and escapement error resulting from variation in amplitude of pendulum swing. Table 2 gives the result of testing over 12 weeks. The test clock was in a grandfather clock case. The average daily variation is ±.008 second per day—a significant improvement over the Reifler Model A running in air and comparable to the Model D clock in a vacuum



PETER G. SCHREINER.

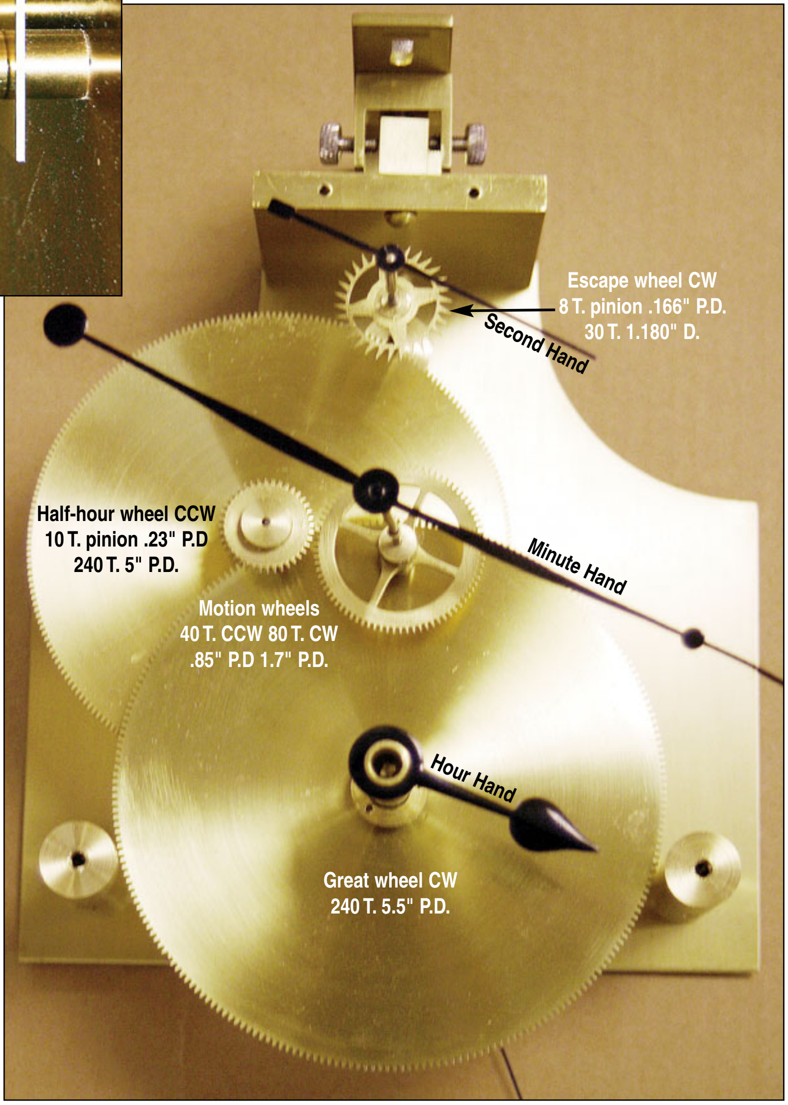
chamber. It uses no jeweling, no electric winding, and no vacuum chamber, and it has a minimum of parts. A closer look at the gear train, the pendulum, and the escapement shows how this result was achieved with a clock that has less complexity than Riefler's design.

The Gear Train

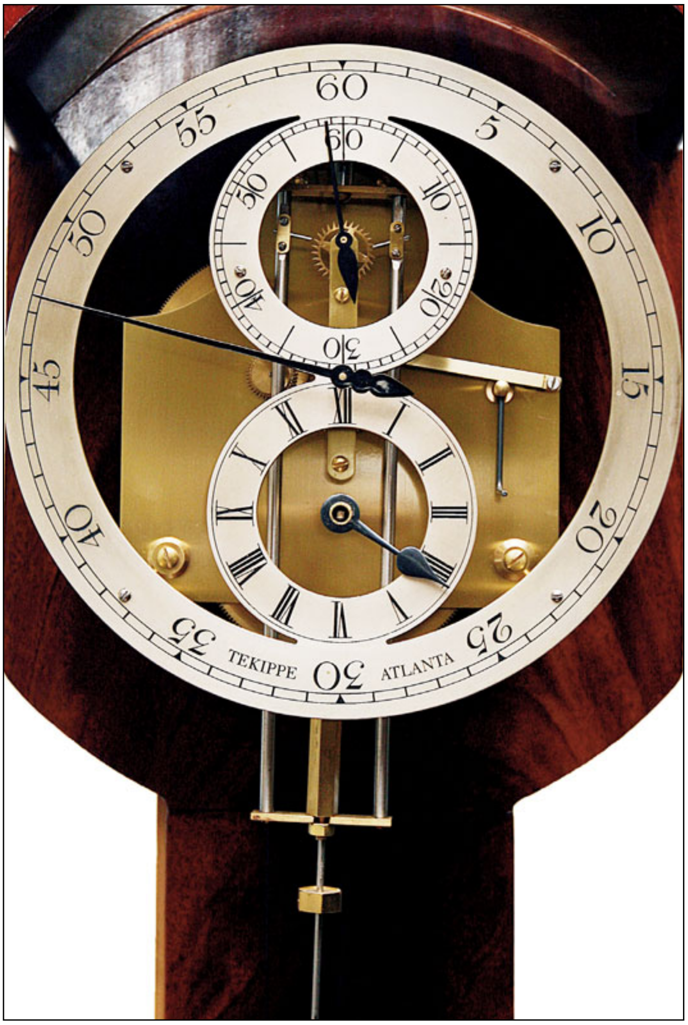
The purpose of the gear train is to transfer the energy of the falling weight to the escapement slowly and smoothly, keeping the clock running as long as possible. At the same time, it must drive the hands to indicate the time. In the gear train there are two sources of friction: the bearings where the steel shafts turn in the brass plates and the wheel teeth as they meet and transfer energy from one wheel to the other. Because the friction in the bearings is so large compared to the friction at the wheel teeth, a minimum number of wheels should be used. In this clock there are three wheels: a one-minute escape wheel, a half-hour wheel, and a 12-hour great wheel. See Figures 1 and 2. The gear ratios of 30:1 and 24:1 are much higher than usual. The escape wheel carries the second hand. The half-hour wheel turns counterclockwise, and the shaft extends through the plate and carries a wheel on the front of the plate. This engages with a wheel with twice as many teeth on a shaft in the center of the dial, which carries the minute hand. This 1:2 ratio causes the minute hand shaft to turn clockwise once an hour. These two gears are called motion wheels and are not part of the main gear train. Their purpose is to drive the minute hand. The shaft of the 12-hour wheel also serves as the barrel. A one-way ball bearing is substituted for the click wheel, click, and click spring. When the great wheel shaft is wound counterclockwise, it turns on the ball bearing; when the weight pulls the shaft clockwise, the bearing locks up and turns the great wheel. The

Figure 1, left. Side view of the gear train with the cord wrapped around the small barrel.

Figure 2, below. Gears without the front plate. The great wheel, half hour wheel, and the escape wheel pinion are mounted behind the front plate. The escape wheel and motion gears are in front of the plate.



BRANDON LONGLEY.



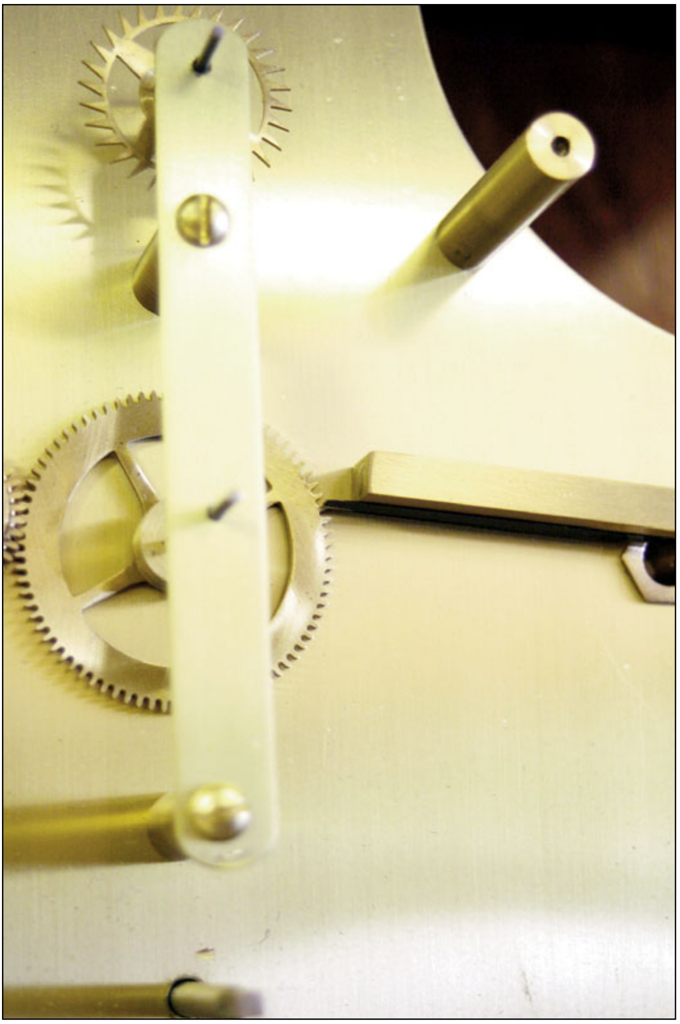


Figure 3, left. Closeup of dial, hands, and key.
Figure 4, right. Closeup of maintaining power lever and spring. Spring is pressing against minute wheel teeth.

shaft is one quarter of an inch in diameter and can accommodate 62 turns of cord, allowing the clock to run for 31 days, with a five-pound weight dropping straight down about 48 inches in a grandfather case. On a wall clock the cord is compounded with a pulley, and a ten-pound weight falls about 24 inches in a month. The shaft extends through the front plate and has a square on the end to fit the winding key and also carries the hour hand.

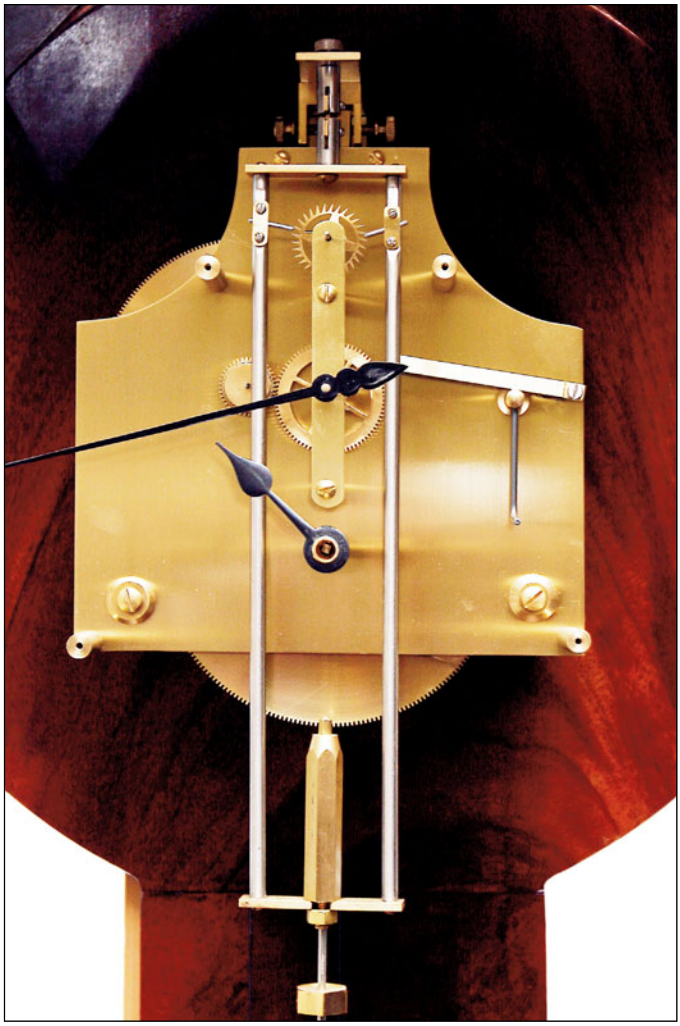
The maintaining power system is also simple. The key is stored in a grommet in the front plate at the 3 o'clock position on the dial. When it is removed to wind the clock, a lever with a piece of flat spring on the bottom presses on the teeth of the minute wheel to provide maintaining power. When winding is completed, the lever is lifted with the key so that the key can be inserted in the grommet and the flat spring bends to bypass the teeth. This can be seen in Figures 3 and 4.

This three-gear train with brass bearings is more efficient than the jeweled-gear trains of previous regulators, which used more gears and pinions with more leaves. It runs on five pounds a month, the equivalent of 1-1/4 pounds a week. Most of the jeweled regulators require more weight than this.

The Pendulum

The pendulum, the heart of the clock, is made of invar, steel, and brass, and designed to swing once a second. It is composed of a top portion connected to the pendulum suspension spring and incorporating the pallets and a bottom portion on which the bob is mounted.

The pendulum suspension spring is mounted to the pendulum support with a short piece of steel rod. See Figure 5. The top of the rod is threaded for a thumb screw and the bottom is slit for the spring. A small screw tightens the slit against the spring. The lower half of the spring is mounted in the same way and connects to the brass strap of the top part of the pendulum assembly. The pendulum spring is a stock item available from the parts suppliers. It was designed for electronic clock movements. It is two thousandths of an inch thick, and the widest standard spring available. This helps to keep the pendulum, with its long bob, from wobbling.[5]



PETER G. SCHREINER (2).

Figure 5, above. The escapement and top of the pendulum. **Figure 6, right.** Full view, the skeleton dial and mahogany case designed to show every detail of the construction. See front cover also.

The top portion of the pendulum is made up of two invar rods screwed to a strap of brass at the top and bottom, which allows clearance for the escape, minute, and hour-hand arbors. The pallets are mounted on these rods and contact the escape wheel teeth directly, without a crutch. The brass strap at the lower end has a U-shaped cutout to mount a brass compensator. This is a 2-1/2-inch-long piece of brass threaded at the bottom and mounted in the U-shaped cutout in the strap with a nut. It is drilled with a 5/32-inch drill except for the top quarter of an inch, which is threaded to fit the 1/8-inch invar rod from the bottom of the pendulum. This compensator elongates upward with increasing temperature and lifts the bottom of the pendulum up, compensating for the downward stretch of the invar. The length of the compensator is adjusted experimentally by trimming until the pendulum has a minimum change in time with a change in temperature.

The bottom of the pendulum is an invar rod carrying the pendulum bob, shown in Figure 6. The bob is a piece of hex brass tapered at the ends. This is a simple shape to make and is related to the parabolic spindles Bateman suggests in his study of the shape of pendulum bobs.[6] Instead of resting on a nut, the bob is threaded and screwed to the pendulum rod and locked in place with a nut. The pendulum is adjusted to be about 30 seconds a day slow, and small weights are added to a tray just below the compensator to make the final time adjustment. These weights are small washers tied to a piece of thread and put on or taken off with tweezers. It takes about a week for the pendulum to settle down, and this system changes the timing without stopping the pendulum.

To compare pendulums, a figure of merit called Q is used. It is a measure of the losses in the pendulum swing from pendulum spring resistance and air resistance. To calculate the Q, the pendulum is hung without the clock and given a swing. The number of whole cycles (to left and back to center and to right and back to center) elapsed while the size of the swing is reduced by half, multiplied by a constant (4.3), is the Q.[7] This pendulum takes about an hour to slow to half, about 1,800 cycles, which gives a Q of 7,740. If the bob is vertical instead of horizontal, the Q is reduced to about 3,800, and twice as much energy would be required to keep the pendulum swinging. The Q could be increased by making the bob out of a higher density material such as tungsten alloy, but cost and other considerations prevented its use in this clock.

The Escapement

The purpose of the escapement is to transfer enough energy to the pendulum to keep it swinging, while trying to disturb its motion as little as possible. This has always been the most challenging part of a clock to design and where there has been the greatest variety of designs. In this clock there are two variations from the usual design. First, the pallets are mounted on the pendulum, and the escape wheel teeth push the pallets and the pendulum directly. See Figure 5. This method has been used occasionally in the history of clockmaking but has never become the accepted practice. It fits in well with the desire to use a minimum of parts and eliminates any friction or variation associated with the verge pivots or crutch. It is hard to argue that driving the pendulum through the verge instead of directly would improve efficiency or accuracy.

The second variation from the usual design is a modification to reduce the errors associated with change in the size of pendulum swing. The driving force on the escape wheel varies with friction in the gear train and results in changes in the amplitude of pendulum swing. This variation, explained by Huygens in 1660, increases as the square of the increase in swing. It can be described as the difference in time of a pendulum swinging the arc of a cycloid and one swinging the arc of a circle. Rawlings was very interested in this subject, and it is a major theme in *The Science of Clocks and Watches*. He said, "It must be remembered that for one reason or another it is very difficult to keep a pendulum swinging with an amplitude which varies so little as one minute of amplitude. Consequently, the variation of circular error may be quite considerable and if we could make an isochronous pendulum we should advance the art as much as Harrison did when he introduced his gridiron pendulum to overcome temperature error."[8] Rawlings suggested an isochronous pendulum because he believed that the majority of the error resulting from a change in amplitude was circular error and that circular error is always greater than escapement error. Many attempts have been made to reduce the variation in amplitude of pendulum swing or to reduce its effect. Jackson and Bush used a spring mounted alongside the pendulum to add additional restoring force when the pendulum amplitude increased. F. M. Fedchenko used a pendulum spring with two outer springs and an inner spring longer than the other two, which gave additional restoring force.[9] Douglas A. Bateman describes an electro-optical method of obtaining a constant amplitude of pendulum swing to eliminate circular error.[10]

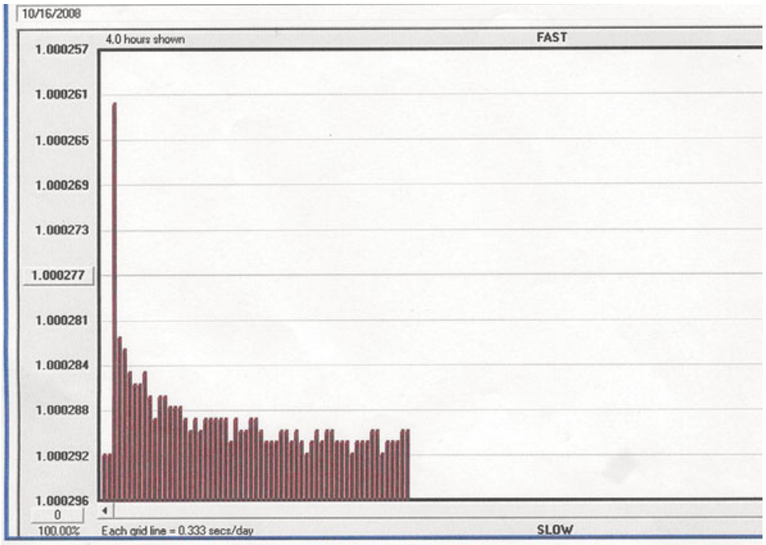
Escapement error is another variation that often occurs with a change in amplitude. This is a change in the speed of the pendulum caused by the escapement as it drives the pendulum. If an escapement drives a pendulum exactly at the lowest point of its swing, it does not speed it up or slow it down. This is also true if the drive is equally before and after center. But if the drive is before center, it speeds up the pendulum, and if after center it slows it down. In 1763 Ferdinand Berthoud knew that he could make a clock that kept better time by modifying the escapement. He describes an experiment with three escapements driving the same pendulum. The escapement with a large recoil sped up the pendulum when the driving weight was increased. The deadbeat escapement slowed the pendulum when the weight was increased. The escapement with just a slight recoil caused no change in the speed of the pendulum when the weight of the pendulum was increased. It was isochronous, the small arcs occurring in the same time as the long arcs. This concept became part of the traditional knowledge among French clockmakers. In his *Traite' d' Horologerie Moderne*, written in 1861, Claudius Saunier is clearly conversant with this idea. It permeates all of his discussion on escapements.[11] The idea is not discussed by clockmakers writing in English. The only mention of it I found is in *Clocks and Watches an Historical Bibliography* by G. H. Baillie. In his review of the *Essai sur l' Horologerie* by Ferdinand Berthoud he says: "The second volume starts with wheel teeth and the calculation of trains. Then follows a long series of experiments on the pendulum, and the effect on its arc and isochronisms of different escapements. From these the author concludes, and probably was the first to conclude, that the aim should be, not an isochronous pendulum, but an isochronous combination of pendulum and escapement."[12]

Escapement error is much better understood now than it was in Berthoud's time. In chapters eight and nine of *My Own Right Time* Woodward gives a very clear presentation of the current understanding.[13] He shows that for a pendulum in a steady state of oscillation, the escapement error can be calculated if we know the phase angle at which the impulse is applied and the Q of the pendulum. It is a complex error, involving impulses before and after center, and frictions before and after center. Until now it has always been approached theoretically, and the part played by the frictions has been hard to estimate.

Adjustment and Performance of the Simple Regulator

In the last ten years electronic timers using a light sensor to time the pendulum swing to a millionth of a second have become commercially available. The Microset Timer by Brian Munford has become the standard used by most experimenters.[14] It is supplied with software to graph the results on a computer. This timer allows a new approach to the study of variations in escapement and circular errors, because it permits direct measurement of them. It is possible to repeat Berthoud's experiment, timing the clock, adding more weight, and measuring the change in time. The result is the sum of the change in circular error and escapement error. Now that it is possible to measure these errors, it is possible to adjust the escapement to minimize them.

It is even possible to distinguish between these two errors, because the change in escapement error happens immediately, and the change in circular error increases slowly as the added energy gradually causes the pendulum swing to increase. The Microset graph immediately displays the escapement error, modified by the change in circular error. This ability to measure these changes in the escapement and circular errors



Graph 1. Changes in period for different driving weights. The large change is when the drive weight is doubled and after about an hour the escapement error and circular cancel to give a rate only 0.1 second faster than the starting rate.

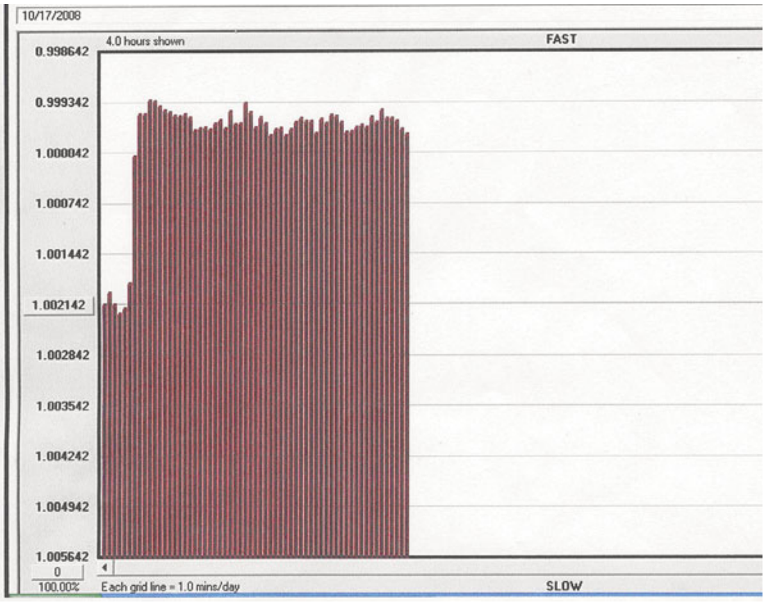
makes it possible to modify an escapement to minimize these variations.

The escapement for the Simple Regulator was designed to have an escapement error that speeds up the pendulum by the same amount as the circular error slows down the pendulum, when the amplitude is increased. In this way these changes in the escapement error and the circular error cancel each other, even as the amplitude varies. The arrangement that gave the best results uses a three-pound pendulum with an amplitude of one degree each side of center. The pallets span 12-1/2 teeth. The deadbeat design is slightly modified with the tip of the entrance pallet lowered a little, and the tip of the exit pallet raised a little to provide a very slight recoil. If the clock speeds up when weight is added, there is too much recoil, and if it slows down, there is not enough. With just the right amount of recoil, there is no change in time when weight is added. Adjusting the amount of recoil causes change in the escapement error, allowing a final adjustment to match the circular error.

Graph 1 shows the result from a test of the Simple Regulator. The graph shows the record of a four-hour period. The scale of the horizontal lines is one third of a second a day. Each vertical bar shows the average time over a four-minute period. The first two bars show the rate the clock has settled down to after several hours of running. The third bar shows the result of adding extra weight. The clock was running on 12 pounds, and an additional 12 pounds were added, doubling the driving weight. The clock speeds up immediately because of a change in escapement error. Gradually, the pendulum swing increases, and the clock slows because of the increase in circular error. It slows until it is only about one tenth of a second faster than before the extra weight was added. The clock design has worked as intended, showing almost no change in time even with such a large increase in weight. The changes in driving force resulting from a variation in friction in the gear train in the normal running of the clock would have a very small effect on the timekeeping.

The graph also indicates the need for a gear train that provides as constant a driving force as possible because the escapement error and the circular error will never cancel completely, and there is always a time period before the circular error catches up with the escapement error. The higher the Q of the pendulum the smaller the change in escapement error will be, and the longer it will take for the circular error to catch up.

This same test can be applied to any weight-driven pendulum clock. As a further demonstration, a Herschede grandfather clock was tested. This is a clock designed just after 1900, and the escapement is similar to the typical regulator clocks of the time. It has a deadbeat escapement, swinging two and one-half degrees each side of center. The clock uses a four-wheel gear train with maintaining power, driven by a 12-pound weight. The pendulum is a four-pound lenticular bob supported on a flat steel rod. Graph 2 shows the result of the test. The scale of the horizontal lines is now one minute per day. After the fifth bar, the weight was increased to 24 pounds. The escapement increases the rate of the pendulum by almost four minutes a day. The circular error eventually reduces this to about three and one-half minutes per day. The escapement error is very large and is not cancelled by the circular error. Even with the smaller



Graph 2. A similar experiment with a Herschede clock. The rate change is about 3.5 minutes a day, two thousand times as large as the rate change for the Simple Regulator.

changes in drive resulting from changes in friction in the gear train in normal operation, the escapement error is probably responsible for the largest variation in the timekeeping of this clock. The escapement error is also larger than the circular error, which Rawlings calculated would never happen.

Summary and a Look to the Future

The very small change in escapement and circular error with a change in driving force is the most important development in the Simple Regulator and the reason for its excellent timekeeping. The changes in escapement and circular errors have been reduced to the point that they are no longer the largest errors in the clock. Almost certainly the largest remaining error is barometric error and the clock could be improved with barometric compensation. Speaking of the best results ever obtained with a pendulum clock, Woodward states, "For a seconds pendulum…the fractional time variation works out at about 0.6 ppm, or twentieth of a second a day, which is as good a result as is ever obtained by a pendulum in air." and on the same page, "…accuracy in air remains stubbornly at a level not much better than half a part in a million, even after correcting or compensating for the variation of barometric pressure."[15] The Simple Regulator varies only 0.01 seconds per day, about one fifth of this amount. It varies less than any other clock without barometric compensation because of its very small changes in escapement and circular errors.

When Reifler and Herschede designed their clocks, it was not possible to measure the changes in circular error and escapement error when the pendulum amplitude changed. There is a consensus among clock designers that this is the largest variation remaining in precision clocks. The escapement of the Simple Regulator does not completely eliminate these variations. It is just a first attempt to set one against the other. Much more experimentation can be done to exploit the precision time interval measurement techniques that are now available. The concepts of using fewer gears with higher ratios and using a pendulum with a smaller swing driven directly by the escape wheel can be developed in many different ways.

The design of the Simple Regulator is presented here so it can be further developed.

Notes

1. Derek Roberts, *Precision Pendulum Clocks: France Germany, America, and Recent Advancements* (Atglen, PA: Schiffer Publishing Ltd., 2004): pp. 138-139.

2. Willis I. Milham, Ph.D., *Time and Timekeepers* (New York: The Macmillan Company, 1942): p. 338.

3. A. L. Rawlings, *The Science of Clocks and Watches,* 2nd edition (New York: Pitman Publishing Corporation, 1948).

4. A. L. Rawlings, *The Science of Clocks and Watches,* 3rd edition, edited by Timothy and Amyra Treffry (Upton, England: British Horological Institute Ltd., 1993).

5. *Merritt's 2008-2009 Catalog of Clock and Watch Repair Supplies, Books and Tools* (Douglasville, PA): p. 106, part number P-1560.

6. Rawlings, 3rd edition, pp. 89-94.

7. Rawlings, 3rd edition, pp. 103-104.

8. Rawlings, 3rd edition, p. 56.

9. Rawlings, 3rd edition, p. 57.

10. Douglas A. Bateman, "Accuracy of Pendulums and Many Factors That Influence It," *NAWCC Bulletin*, No. 290 (June 1994): pp. 300-312.

11. Claudius Saunier, *Treatise on Modern Horology*, translated by Julien Tripplin and Edward Rigg (Newton Centre, MA: Charles T. Bradford Co., 1976): pp. 532-534.

12. G. H. Baillie, *Clocks and Watches: An Historical Bibliography* (London, England: N.A.G. Press Ltd., 1951): p. 262. Part of this quotation is also used in the title of this article.

13. Philip Woodward, *My Own Right Time* (Oxford, England: Oxford University Press, 1995): pp. 63-81.

14. Munford Micro Systems, 3933 Anton Road, Santa Barbara, CA 93110. timer@bmumford.com.

15. Woodward, p. 134.

About the Author

I started collecting and repairing clocks in 1967 at the age of 25. In 1969 I became a member of the NAWCC and immediately signed up for a "ten-year program" in the NAWCC school of clock repair. Back then there was no formal classroom instruction, and it took longer to learn the craft. Speakers at our chapter meetings were our teachers, and the speakers at regionals, national conventions, and seminars were like visiting professors. Atlanta Chapter 24 had many experienced members eager to share their knowledge with new members.

In 1970 I began to repair clocks for customers, and in 1975 I left a teaching career in the computer industry to earn my living in the clock business. I opened Classic Clocks in Atlanta, which I still operate. I bought and sold clocks, but specialized in repairs. I obtained a large lathe and a milling machine adapted for gear cutting from a clockmaker's estate and several professional machinists in Chapter 24 taught me to use these machines.

In 1980 I began to teach clock repair to new members and to speak at chapter and regional meetings. Presenting the information in an organized and interesting way required a lot of study and was part of my continuing education. In 1981 a group of Chapter 24 members met at my shop to build clocks and then demonstrated the process at a regional meeting. None of us had any experience making a clock—we were a self-help group. We built 14 lighthouse clocks, and donated one to the NAWCC Museum. We met every Monday night for sixteen years and built eleven different clock designs. Four members of this group attended the 1983 seminar in Cleveland, OH, on precision clocks, and this seminar determined the direction of my future study.

In 1997 I began original research with the aim of making a significant contribution to the literature on precision timepieces. One result is the clock presented in this article. I would appreciate your questions, comments, and criticism. I can be reached at bernie@classicclocksatlanta.com.