Forecast:
Results like clockwork

The Relaxation Times

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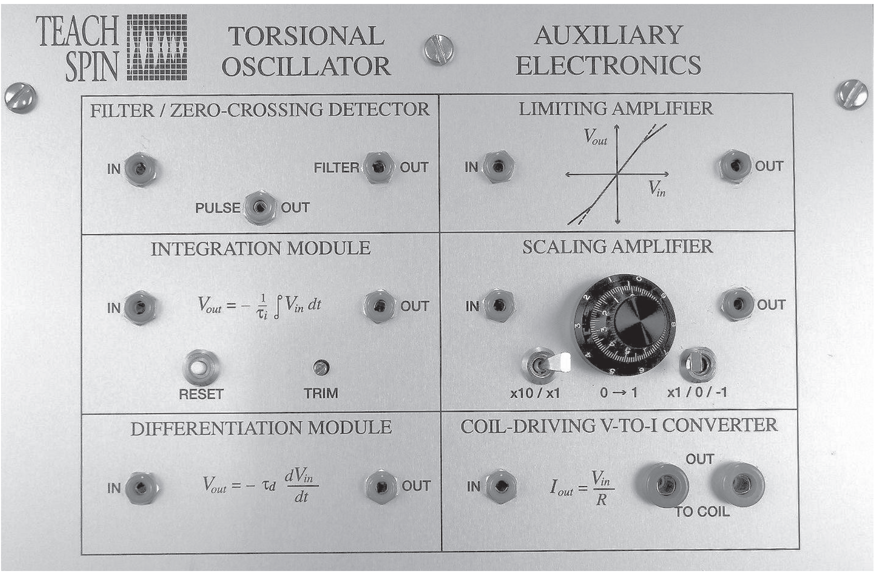
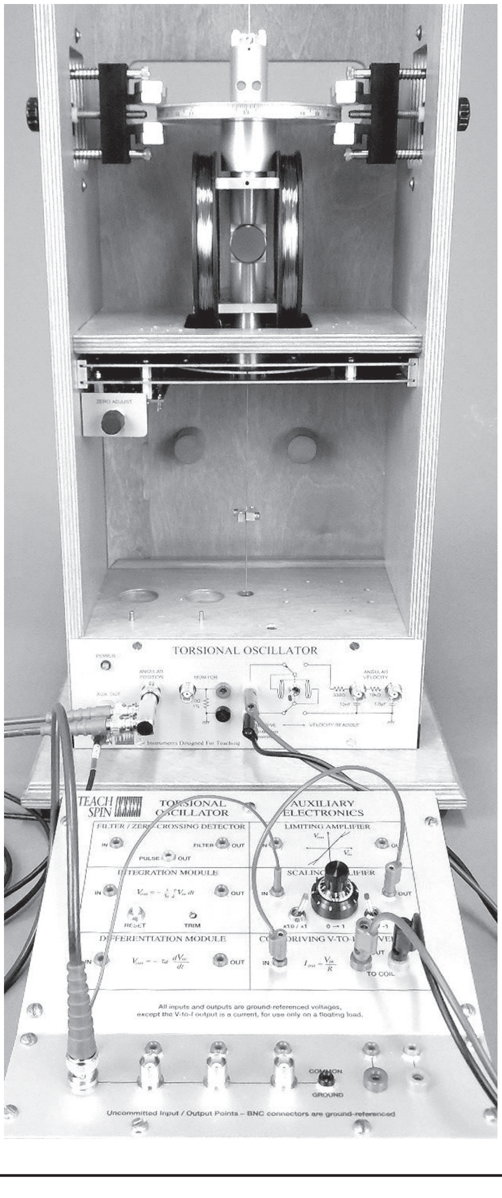
Examining *Feedback* Using the Torsional Oscillator

Students in physics learn about “feedback” in various ways. Some know the term from its unintended consequences in public-address systems. Some learn its remarkable applications in operational-amplifier electronics. Others see it applied to servomechanisms, such as temperature regulators. But now we’re offering a chance to teach and learn feedback with unusually visible, tangible, and useful consequences in an electromechanical context: This Newsletter announces the debut of the Auxiliary Electronics that bring the feedback concept to bear on our Torsional Oscillator. Students will thus see examples of feedback in action and learn why feedback is so useful in instrumentation and measurement in general, because of the ways it can modify and improve the behavior of a physical system.



Auxiliary Electronics is our name for a single box containing six independent analog-electronic modules. We provide convenient and versatile ways to interconnect them to each other and to the outside world, so students will find it easy to test their own feedback configurations. Power for the Auxiliary Electronics (AE) box is provided by a cable that connects to that previously mysterious 4-pin AUX OUT connector that’s always been built into the front panel of our Torsional Oscillators (TO). Students’ basic use of the AE is to take the TO’s ‘Angular Position’ output, to modify that electronic signal suitably using the modules of the AE, and then to feed the modified signal back into the TO’s ‘Drive Coils’.



Students will be surprised by the variety of investigations they can explore using this sort of electro-mechanical feedback. Here we present only two of many examples.

1.) An Electronic "Torque Meter" - A passive Torsional Oscillator responds to a steady external torque τ by showing a steady-state angular deflection, $\Delta\theta = \tau/\kappa$, where κ is the torsion constant of the fiber. A visual, or electronic, readout of that angle is thus a surrogate measure of the torque being applied.

The tools in our TO plus Auxiliary Electronics allow a different way to measure such a torque. We arrange to sense a torque-caused departure from $\theta = 0$, and then to modify the electronic version of the resulting angular-position signal, feeding that back into the TO's drive coil. The process is devised to find just the right (magnetic) counter-torque that restores the torsion fiber to its previous $\theta = 0$ condition. The drive-coil current needed to produce this counter-torque is then an indirect measure of the external torque being applied to the device. [An analogous 'force replacement' or counter-force technique is used in many electro-mechanical one-pan balances, to give a measure of vertical force, namely the weight of an object put onto the balance's pan.]

This feedback technique has dramatic instrumentation advantages, automatically ensuring a sort of time-averaging. It furthermore relaxes any requirement of linearity of the angular-position transducer (or indeed, of the fiber's response to torque), as it depends instead on the linearity of the required counter-torque in the current which produces it.

Below we show both techniques in operation, detecting a torque which alternates between the two values of $\pm 19 \times 10^{-6}$ N·m, during a 10-s period. (That torque arises from a 0.1-Hz square-wave current in a distant coil.) The direct detection of this tiny torque is possible, as seen in the left-hand image. Either by the scale of this signal, or from the known physics of our torque excitation, we can tell it's causing a mere ±0.33 milli-radian displacement of the TO's rotor (which translates to a motion of ±20 micrometers at the rotor's periphery). The detection of this torque via the feedback technique has dramatic signal-to-noise advantages, as shown in the bottom trace of the right-hand image.

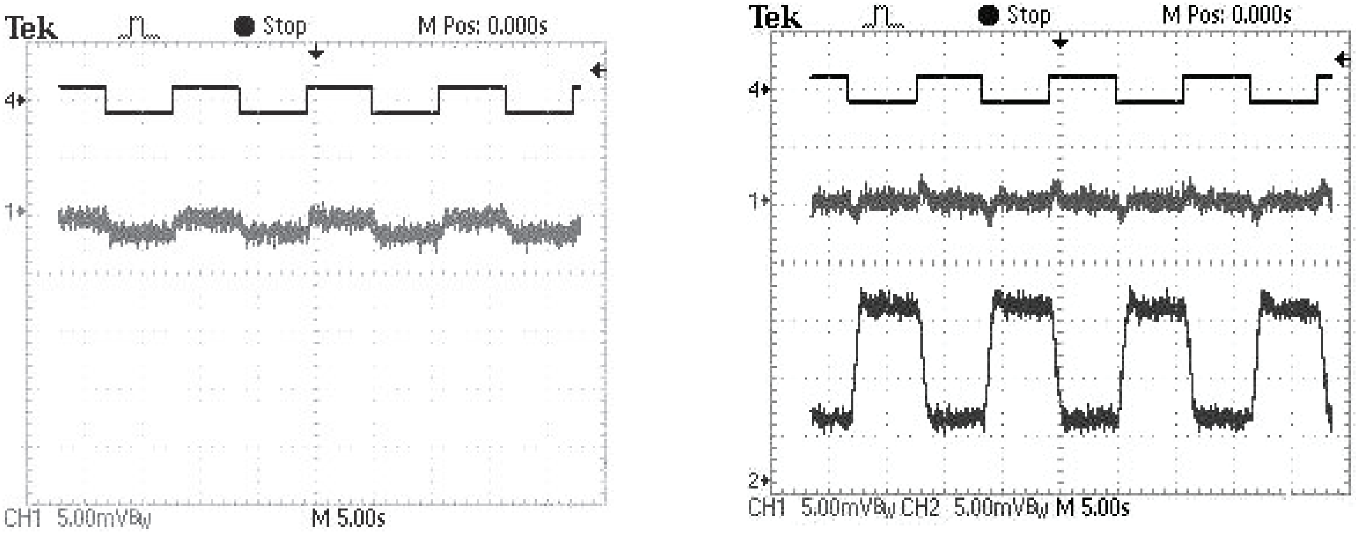


Fig. 1: (Left, using direct detection) Top trace, the torque 'cause' signal; below it, the angular-position 'effect' signal from the TO. (Right, using detection via feedback) Top trace, again the torque 'cause' signal; below it, the angular-position signal, now being servo-driven to zero; at the bottom, the detection of the external torque via the counter-torque signal generated in the Auxiliary Electronics.

2.) A Torsional Clock - One might view the previous example as a case of using feedback to modify the effective stiffness of the torsional fiber in our TO – all the way to the $\kappa_{\text{eff}} \rightarrow \infty$ limit of defeating any actual deflection $\Delta\theta$ under a torque load.

But feedback can be used to modify things other than the torsion constant. Alternative uses of the new Auxiliary Electronics can create, instead, an effective change in the damping constant of the rotational oscillatory motion. For a faster 'settling time' of response, some users might want, via such feedback, to augment the damping already present. Even more glamorous is to use feedback of the opposite sign, to reduce the damping all the way to zero.

How does the torsional oscillator then respond? As a now entirely undamped simple harmonic oscillator, it evolves from any initial displacement θ_0 to a steady-state waveform $\theta(t) = \theta_0 \cos \omega t$. Here $\omega = \sqrt{(\kappa/I)}$ is the 'natural angular frequency of undamped motion'. In a word, the TO-with-feedback runs as a *clock*, with period $T = 2\pi/\omega$. For the as-shipped TO devices, we find T ≈1.16 s (easily changed, by adding masses to the rotor to change *I*, or by changing the fiber to vary κ). Yet reading that period to two decimal places scarcely begins to do justice to our clock's performance – an electronic counter can measure that period with microsecond resolution. What do such readings reveal? Here's a first example of some time-keeping by our TO-as-clock. Each point plotted below gives the electronically-measured duration of successive full cycles of our clock. You see that out of a period of about 1,166,600 µs, the repeatability of these open-air results is about ±20 µs. But what is that offset visible in samples numbered 7 through 13 in the data below? What made the period rise by nearly 400 µs? The answer is: those were data points taken while the rotor of our TO was loaded with some extra mass, via the addition (and then the removal) of a tiny brass washer, of mass about 0.40 g.

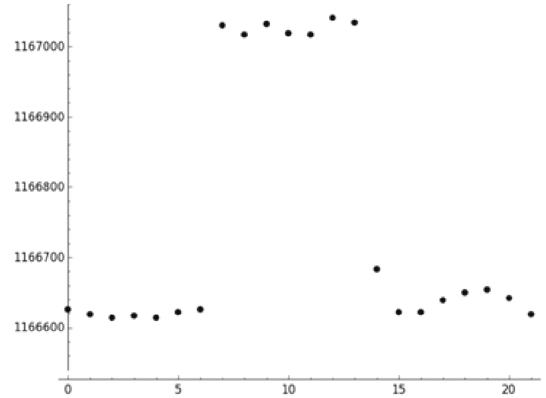


Fig. 2: Measured duration of successive periods of the autonomously-running torsional clock. Vertical scale gives period, in µs; horizontal scale gives the ordinal number of the period measured.

Adding this mass near the periphery of our ≈1 kg solid-copper rotor raises its rotational inertia by about 0.08%, and thus increases the clock's period by about 0.04%, or 400 parts per million, a small effect yet still detected with signal/noise ratio well above 20. This technique is analogous to that used in mass-deposition monitors vital in the field of vacuum deposition, in which the addition of mass raises the period of oscillation of a vibrating quartz crystal. As in such cases, so also in our TO: the deposition (and removal) of the mass can be done in real time, while the system is undergoing continuous oscillation.

If we can so readily detect a 400-ppm effect with a torsional clock, what else can we do? Here's another experiment in small-effect detection. Users of our TO will understand why one horizontal component of the ambient magnetic field (call it B_h) will create an extra restoring torque on the permanent magnet mounted on its rotor. But that effectively changes the torsion constant κ of the fiber, and thereby affects the period of the TO running as a clock. Below we again plot some measured periods of the clock, as a function of the extra horizontal field ΔB_h that we've added via an external source of field. In the plot below it's easy to see the ≈100-ppm effect arising from field changes of size 1 µT (or 10 milli-gauss). With a bit more averaging, we've resolved 50-fold smaller field changes. Not many devices, of any kind, can detect such 0.2 milli-gauss or 20-*nano*Tesla field changes! Your students might be surprised to see that a steampunk-looking wood-and-copper electro-mechanical contraption can exhibit sensitivity this high.

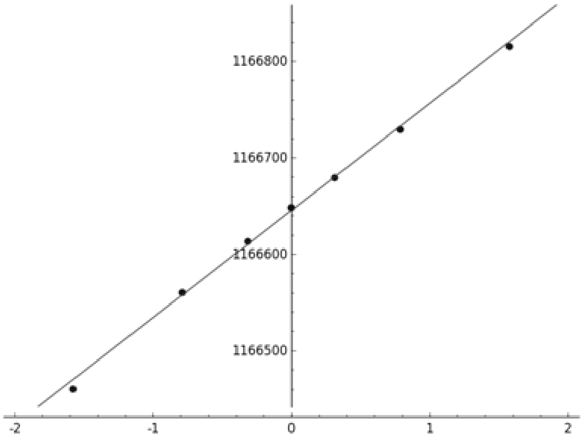


Fig. 3: Measured period of the autonomously-running torsional clock, as a function of externally-imposed magnetic field; each point plotted is derived from averaging four single-period measurements. Vertical scale gives the clock period, in µs; horizontal scale is the added horizontal field, in µT. The line guides the eye.

As usual, we've devised a Manual for our TO Auxiliary Electronics which takes students through its many uses. We've paid special attention to the transferable skills that can be taught using these devices. We've also taken care to guide students in the use of differential equations to model everything that's going on, even in the presence of feedback. We're ready to ship these TO-AE units, at a time-limited introductory price of $785. We hope you and your students will find these capabilities, and their results, as captivating as we have.

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Our New Auxiliary Electronics
for Torsional Oscillator TO2-A
makes *feedback* teachable

It's finally
Here!

TeachSpin will be exhibiting at the **APS MARCH MEETING**
the fruits of a multi-year development effort,
giving your students access to a field of physics
that's been neglected up to now.

Congratulations

Announcing the first awards under the AAPT-ALPhA Prize

This award, established in 2015 and funded by TeachSpin, recognizes ***"undergraduate physics students who have built (and possibly designed), and left a legacy for future students, an advanced laboratory experiment".*** Nominations are now open for prize-worthy accomplishments of your 2017 students.

Ryan Scott
(then of Rochester Institute of Technology)
for *"The Hong-Ou-Mandel Effect"*

Brandon Thacker
(then of California State University, Chico)
for *"The Mechanical Chaotic Oscillator"*

See **http://www.aapt.org/Programs/awards/aapt_alpha_award.cfm** for more details on this new prize