Newtonian Labs

Magneto-Mechanical Harmonic Oscillator

Instrument Description

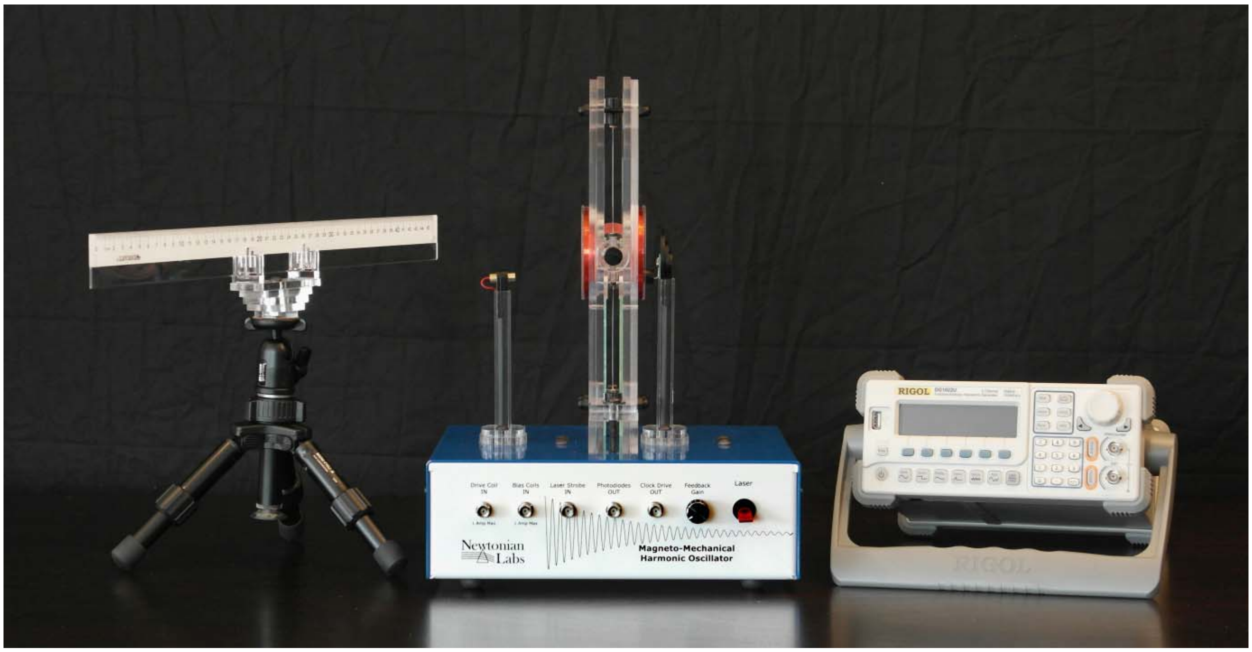

Figure 1. The Magneto-Mechanical Harmonic Oscillator instrument package includes everything you see here, together with full documentation and a comprehensive instruction guide.

I. Introduction

The Magneto-Mechanical Harmonic Oscillator (MMHO) was designed for teaching the physics of the Simple Harmonic Oscillator at an introductory level, with a particular emphasis on high-Q oscillators and clocks.

Since harmonic oscillators play such a central role in modern physics, and high-Q mechanical clocks (in the form of micro-machined quartz crystal oscillators) are omnipresent in today's electronic devices, the MMHO experiment introduces students to a fascinating and vital area of physics and technology.

We have strived to make the MMHO instrument easy and fun to use, with an open and intuitive feel. The hardware is ruggedly built and the oscillator parameters were chosen with student interaction in mind. Using the MMHO apparatus, students can collect accurate data quickly and reliably, learning the physics through a variety of quantitative and qualitative investigations.

This document describes and illustrates the hardware in the MMHO instrument. For additional information, see also our **Guide to Experiments** and our **Physics of the Magneto-Magnetic Harmonic Oscillator** documents, both available at *NewtonianLabs.com*.

Figure 2. A front view of the MMHO, with two optical paths digitally added to the image. On the left, a red laser reflects off one of the test-mass mirrors and onto a ruler surface (not shown here). On the right, light from a white LED reflects off the other test-mass mirror and onto a pair of photodiodes.

II. The Oscillator

Figures 2 and 3 show some of the mechanical features of the MMHO. At the center of the instrument is a torsional oscillator with a resonant frequency of about 40 Hz and a mechanical Q that can be adjusted from about 100 to 2000. The central test mass is supported by two vertical steel wires, and the twisting of these wires provides a restoring torque for the oscillator. We tested one oscillator for over a half trillion cycles without any signs of metal fatigue in the wires.

The test mass includes a 0.5-inch-diameter cylindrical rare-earth magnet, with the axis of the cylinder mounted horizontally (see Figure 3). The magnetic dipole axis coincides with the axis of the cylinder. The test mass magnet is

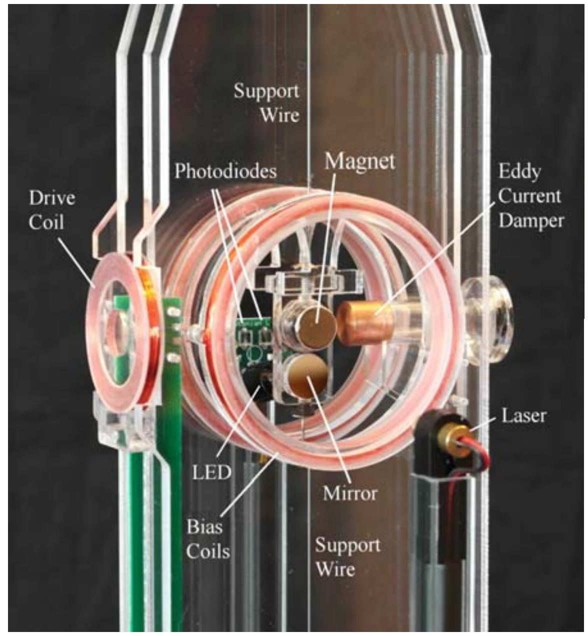

Figure 3. A close-up view of the central oscillator. Note that the open construction and clear housing give interested student an excellent view of the hardware from all angles.

held in an acrylic mounting plate, and just below the magnet are two round mirrors, one on either side of the plate.

The torsional oscillator is excited magnetically using the drive coil shown in Figure 3, for example with a sinusoidal signal from the Rigol 1022 function generator (included in the MMHO package). The drive coil produces a magnetic field that is perpendicular to the magnet moment of the test mass, yielding a torque $\tau = \mu x B = \mu B$ (at small angles). Thus to good accuracy the drive torque is simply proportional to the drive current, which in turn is proportional to the drive voltage.

The MMHO instrument also includes a removable eddy-current damper (see Figure 3). This is simply a copper cylinder that is placed near the test mass. The moving magnet generates eddy currents in the copper that damp the oscillations. The mechanical Q of the oscillator can be adjusted over the range 100-2000 by positioning the eddy-current damper.

In typical operation, the MMHO is very well described by ideal Simple Harmonic Oscillator (SHO) theory. The spring constant is accurately linear, the test mass is a single rigid body (in particular, the moment of inertia of the spring wires is completely negligible), and the damping is simple linear velocity damping.

Also shown in Figure 3 is a pair of bias coils. These coils produce a magnetic field along the magnetic axis of the test mass. This field exerts a torque $\tau = \mu x B = \mu B \sin\theta = \mu B\theta$, where again we have used the small angle approximation.

One can use the bias coils to change the spring constant of the oscillator, which becomes $\kappa = \kappa_0 + \alpha I$, where κ_0 is the spring constant from the wires alone, I is the bias coil current, and α is a constant. Depending on the sign of the current, the spring constant can either be increased or decreased.

III. Measurement Methods

The oscillatory motion of the test mass is measured optically via two methods. In the first, a red laser beam reflects off one of the test-mass mirrors and produces a clearly visible laser streak on a graduated white ruler, as shown in Figures 2 and 4.

The laser streak provides an excellent visual indicator of the oscillator amplitude. The beam geometry is instantly clear, and students can trace the light path by placing a white card at various points in the beam. The calibration yielding the angular displacement of the test mass follows directly from the beam geometry.

The laser streak is also a surprisingly accurate measuring tool. The length of the streak on the ruler is perhaps 200 mm, and the markings on the ruler allow simple length measurements by eye that have an accuracy of 1 mm or better.

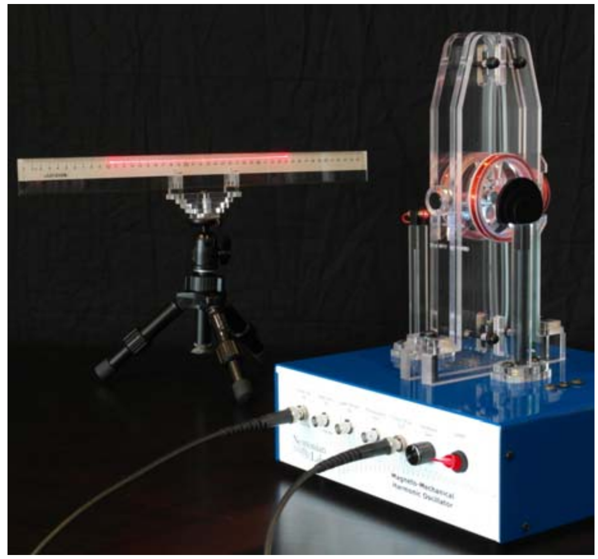

Figure 4. When the test mass is oscillating, the reflected laser produces a visible laser streak on a graduated white ruler. The length of the streak can be measured by eye to an accuracy of 1 mm or better, and a simple geometrical calibration yields the oscillator amplitude in radians.

The second method for measuring the test mass motion uses an LED that bounces a broad beam of light off the second test-mass mirror and then onto a pair of photodiodes (see Figures 2 and 3). At zero angular displacement, the beam is centered between the photodiodes, while nonzero angular displacement sends more light to one photodiode or the other. Differencing the two photodiode signals yields a voltage that is proportional to θ(t), the position angle of the oscillator as a function of time.

Figure 5 shows how the two optical methods complement one another when measuring the oscillator amplitude. The laser streak yields measurements that are geometrically calibrated and especially accurate at high amplitudes, when the streak is long. The photodiode signal saturates at high amplitudes, but has excellent linearity and much superior sensitivity at low amplitudes. Together the two methods give accurate measurements covering over three orders of magnitude in the amplitude.

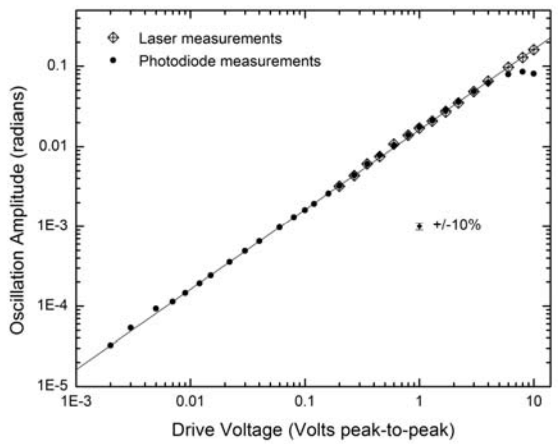

Figure 5. Measurements of the oscillator amplitude as a function of the drive voltage, using the two optical methods described in the text, together with a linear fit line. Here the laser measurements were used to calibrate the photodiode signal. At the lowest amplitudes the measurement accuracy is limited primarily by seismic noise.

IV. Clock Drive

Another feature of the MMHO is its "Clock Drive" mode, in which the oscillator becomes self-exciting, oscillating at its own resonant frequency. This works via a simple feedback mechanism, where the oscillator signal itself is fed back to the drive coil. The clock drive signal is directly accessible to students, leading naturally into an enlightening discussion about feedback, self-sustaining oscillations, and how essentially all clocks function.

Figure 6 shows an oscilloscope screen displaying the photodiode and clock-drive signals. The red trace is the photodiode signal that shows $\theta(t)$, the position angle of the oscillator as a function of time. Circuitry inside the MMHO chassis takes this signal and derives the Clock Drive signal shown by the yellow trace in Figure 6. This signal is then sent to the oscillator drive coil.

In Clock Drive mode, every time the oscillator goes through $\theta(t) = 0$, the drive coil gives it an impulse that keeps the oscillations going. Because the pulses are brief and the oscillator Q is high, the oscillation frequency in clock mode is equal to the resonant frequency of the oscillator to better than 0.1 percent.

Figure 6. An oscilloscope screen-shot showing the sinusoidal photodiode signal (red trace) and the pulsed Clock Drive signal (yellow trace).

V. Intuitive controls

The MMHO front panel controls are shown in Figure 7. Like the instrument itself, these controls are designed to be intuitive and easy to use. They include:

Drive Coil IN – connected directly to the drive coil. The coil inductance is typically negligible, so the coil acts like a low-impedance (resistive) input. The coil current is then determined in large part by the output impedance of the drive signal, for example the 50-ohm output impedance of the Rigol signal generator. The intuitive final result is that the driven oscillator amplitude is simply proportional to the drive voltage, as shown in Figure 5.

Bias Coil IN – connected directly to the bias coils.

Laser Strobe IN – a pulsed signal can be fed into this port to strobe the laser on and off. By strobing close to the oscillator frequency, one can better visualize the oscillations. This input is buffered, so just about any pulsed signal can be used.

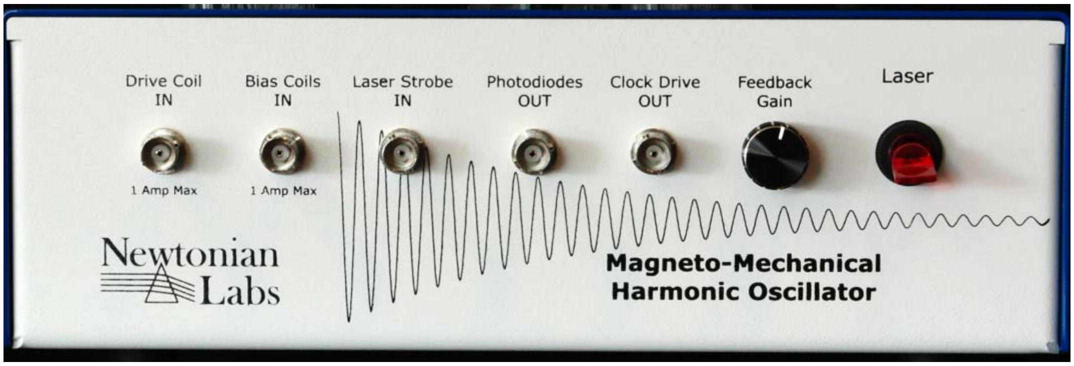

Figure 7. The front panel of the Magneto-Mechanical Harmonic Oscillator chassis.

Photodiodes OUT – this gives the photodiode difference signal. At low oscillator amplitudes, this signal is proportional to the oscillator position angle $\theta(t)$. Calibration is provided by making simultaneous measurements using the laser streak. At large amplitudes, $\theta \sim 0.05$ radians or greater, the photodiode signal saturates, so is no longer simply proportional to $\theta(t)$.

Clock Drive OUT – the clock drive signal, for example the yellow trace shown in Figure 6. In Clock Drive mode, this output is connected directly to Drive Coil IN.

Feedback Gain – this knob changes the amplitude of the Clock Drive signal, and thus the amplitude of the self-excited oscillator.

Laser – a power switch that turns the laser and LED on/off.

Figure 8. The MMHO instrument package includes a Rigol 1022 arbitrary function generator, with a frequency resolution of 1 μHz.