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High performance laser shutter using a hard disk drive voice-coil actuator

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Voice-coil motors in computer hard disk drives are shown to make excellent mechanical shutters for light beams. Shutter speeds in excess of 10 mm/ms are attained, allowing switching of a focused beam in under 10 μ s. Aperture size can be up to 32 mm. As little as 1 mW of power is required for shutter operation. The shutter can be driven with a sinusoidal signal to switch at up to 100 Hz. The shutter is also suitable for x-ray applications. Essentially no modification of the drive or actuator is required for most types of operation.

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Many laser-based experiments require fast switching of laser beams. Several commercial products and lab-designed systems are available for this purpose, each with various performance trade-offs. Acousto-optic and electro-optic devices offer switching times of less than 1 μ s, but require careful alignment and do not provide 100% transmission and extinction. Commercial shutter systems close at speeds up to 25 m/s, and switching times of less than 1 ms, but are expensive, require large power supplies, and have limited aperture sizes.¹

Adams² used a piezoelectric actuator to operate a shutter with switching times of 10 μ s, but with limited displacement, of order 10 μ m. Careful alignment of the lens system was required so that the shutter could close across the beam waist, and extinction and transmission were incomplete. The displacement could be enlarged by attaching pivot arms to the piezoelectric actuators, but this would increase complexity and reduce shutter velocity. Another system³ used resistance heating and expansion of a NiCr wire to displace a shutter flag. A high current capacitor discharge achieved an activation time of less than 300 μ s, but the shutter was limited by its slow relaxation time. Voice coil systems using adapted loudspeakers offer fast extinction, but again, over a limited shutter area.⁴

In this article we investigate the adaptation of a standard hard disk memory storage device to provide a low-cost fast laser shutter. Modern computer hard disk drives use voice-coil motors to move a read-write head across the surface of a rapidly rotating magnetic media platter. These rotary or swing-arm actuators are capable of very large accelerations (greater than 20 g) and positioning accuracy of better than 100 nm. In the common 3.5 in. hard drive format the read-write head has a travel range of up to 32 mm. Modern drives have full transit times of less than 20 ms, corresponding to an average linear velocity of 1.6 m/s. These sophisticated high-performance electromechanical actuators are readily available at no cost, from otherwise defunct computer hard drives.

A hard disk drive consists of two major mechanical components: the data storage area, normally aluminum or glass platters with a ferromagnetic coating, which are mounted on a central spindle motor; and the read-write head assembly, a pivot arm that moves the head over the full width of the data platters.

The read-write heads are mounted at the tip of triangular metal pivot arms. On the opposite side of the pivot axis sits a tightly wound trapezoidal coil of copper wire, positioned between rare-earth magnets. The coil-magnet assembly is the voice coil actuator (VCA), which controls the position of the read-write heads. The actuator is contained in a steel assembly, or “keeper,” which constrains the magnetic field through the coil.

The poles of the magnets are arranged such that the field lines point in opposite directions at each end of the assembly, parallel to the coil normal. The looped coils direct the current so that there is a net force in the actuator in a tangential direction. During hard disk operation the current is carefully controlled by high-precision closed-loop servo circuits, enabling positioning of the read-write heads to an accuracy of better than 100 nm.

Several shutters were constructed from otherwise defunct 3.5 in. hard drives. Detailed measurements were made using a particular drive⁵ of standard 3.5 in. format, with two heads and one platter, and an average seek time of 10 ms. Almost all hard drives, including those no longer functional as data storage devices, are suitable for conversion to a shutter. We have successfully adapted drives from 2.5 to 5.25 in. format for shutter operation. An example of a modified 3.5 in. drive is shown in Fig. 1.

The shutter was formed by a 30-mm-square flag, constructed from 50- μ m-thick steel, attached to a pivot arm with epoxy adhesive. The head assembly typically has multiple parallel pivot arms, one pair for each storage platter. Only one arm is required for the shutter, so all others were removed to reduce inertia and maintain balance. The majority of the hard drive case was also removed so that the laser beam could pass unimpeded within the entire sweep of the shutter arm. The maximum sweep range is set by the range of movement of the voice coil within the magnet assembly, typically 25–32 mm.

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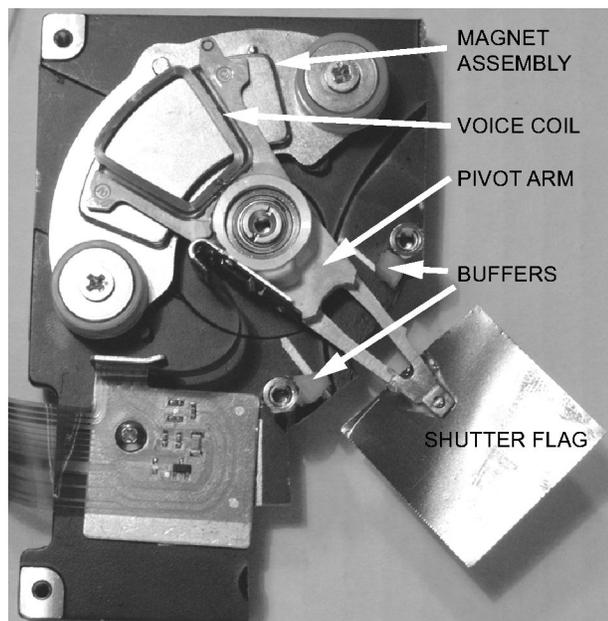


FIG. 1. The VCA shutter, with the top half of the keeper removed to show the voice coils.

The sweep of the shutter arm was constrained slightly by placing elastomer buffers at each edge of its range of movement. The buffers reduce vibration within the shutter and prevent impact damage to the voice coils.

The shutter arm has no preferred location and no internal spring. The power requirements are extremely small, needing only 1 mW to swing the shutter open and closed in a fraction of a second. The minimal energy demands allow the shutter to be run from a small battery. This mode of operation is suitable for use as a laser safety shutter.

For fast switching, the shutter was driven bidirectionally from a unipolar power supply in a two-stage process using the modified metal-oxide-semiconductor field effect transistor H-bridge circuit shown in Fig. 2. The voice coil is held at either extreme of its travel range by a current of approxi-

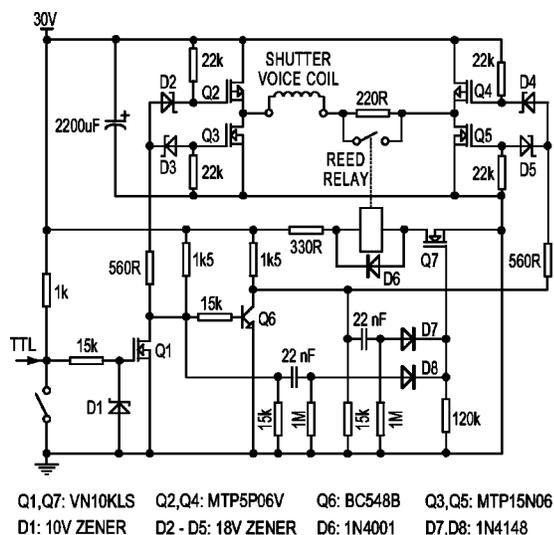


FIG. 2. Bidirectional electronic driving circuit for the shutter using a unipolar supply. The shutter can be toggled using the switch or a TTL compatible signal.

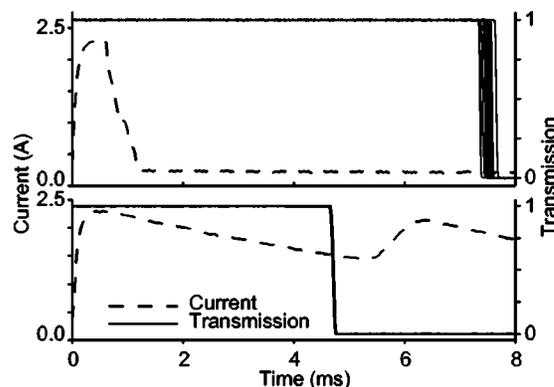


FIG. 3. Shutter jitter. Top plot shows short (1 ms) driving pulse and ten photodiode signals as the shutter passed across the beam waist. The lower plot shows the reduced jitter for increased pulse length.

mately ± 100 mA. The magnitude of this current is governed by the 220Ω resistor in series with the shutter coil, which typically has a resistance of 12Ω . On triggering, the current direction is reversed, causing the voice coil to move towards the opposite end of its travel range.

For maximum shutter velocity, triggering also closes the relay shorting the 220Ω resistor, so that the full 30 V (2.5 A) is temporarily applied to the coil. The relay timing, and hence current pulse length, is controlled by the discharge time of the $120 \text{ k}\Omega$ 22 nF RC combination determining the gate voltage on Q7. On opening the relay, the current drops back to 100 mA, which is enough to move the coil to its extreme position.

For the fastest possible optical switching, the shutter was placed at the focus of a laser beam. The transmission of the shutter as it moved across the waist of a focused He-Ne laser beam was recorded using a photodiode detector. The $1/e^2$ waist of the beam was measured at $30 \pm 1 \mu\text{m}$ using a commercial beam profiler. The shutter was positioned so that it crossed the beam approximately at the center of its travel.

The extinction time depends on the duration of the driving pulse. When the current pulse duration was longer than the shutter delay, then the average fall time (90%–10%) was $6.2 \pm 0.3 \mu\text{s}$. The shutter delay was extremely consistent. Figure 3 shows ten measurements of the fall time across the beam waist for two driving pulse lengths. For a 9 ms driving pulse, the 50% transmission level was reached with a delay of 3.34 ms, with a standard deviation, or jitter, of only $\pm 6.5 \mu\text{s}$ across 50 measurements. When the pulse was turned off before the shutter passed through the beam, the jitter was more pronounced. For a 1 ms pulse the delay was 6.06 ms, with a jitter of $\pm 87.4 \mu\text{s}$.

The shutter velocity was determined by recording the motion of the shutter across an expanded laser beam. The He-Ne beam was expanded using a cylindrical lens and an aperture used to select a 22-mm-wide beam of approximately constant intensity. The beam passed through the shutter and was then focused onto a photodiode. The recorded signal was normalized to the measured intensity distribution before calculating the velocity from the transmission gradient. Extinction signals for the expanded beams are shown in Fig. 4. The gradient of the plots is not constant due to nonuniformity in the intensity distribution of the incident beam, but this was accounted for when calculating velocity. For 1 and 4 ms cur-

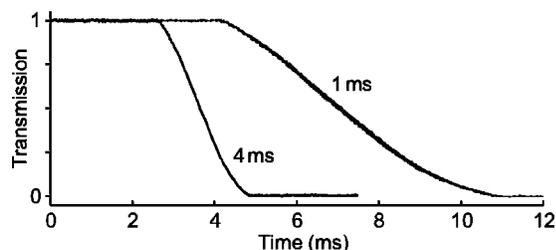


FIG. 4. Optical transmission, used to calculate shutter velocity. The plots show five separate transmission measurements for both 1 and 4 ms current pulses driving the shutter across an expanded laser beam. The gradients correspond to velocities of 3.2 ± 0.1 and 10.1 ± 0.1 m/s, respectively.

rent pulses the shutter reached mean velocities of 3.2 ± 0.1 and 10.1 ± 0.1 m/s.

The shutter was also adapted for use in x-ray applications. A lead plate, of dimensions $24.7 \times 21.5 \times 0.8$ mm was attached to the pivot arm of another hard drive⁶ with epoxy adhesive. Driving pulse durations of 1 and 9 ms moved the shutter at average velocities of 0.61 ± 0.03 and 1.22 ± 0.03 m/s. The total close time (zero to total attenuation) was less than 20 ms for a 22 mm aperture. The lead plate has less than 1% transmission at energies up to 50 keV, and the speed is well within requirements for many x-ray beam applications.

Using a sinusoidal drive current it was possible to use the device as an optical chopper. An L165 high current op

amp was used to drive up to ± 1 A through the voice coil. Operation was stable at up to 30 Hz with minimal phase jitter, and 100 Hz for short periods, limited by overheating of the coil.

With suitable photodetection and electrical feedback circuit, we expect that the shutter could also be used as a rapid and precise variable optical attenuator. The attenuator could be operated with an opaque shutter partially blocking an expanded optical beam as described above, or with a graded neutral density filter in place of the metal blade.

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¹ThorLabs SH05, www.thorlabs.com; Uniblitz LS56, www.uniblitz.com.

²C. S. Adams, Rev. Sci. Instrum. **71**, 59 (2000).

³M. Ye and D. Jiang, Rev. Sci. Instrum. **61**, 2003 (1990).

⁴K. Singer, S. Jochim, M. Murdich, A. Mosk, and M. Weidemüller, Rev. Sci. Instrum. **73**, 4402 (2002).

⁵Fujitsu 2.1 GB drive (model MPB3021AD). Note: certain commercial equipment, instruments, or materials are identified in this article in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the University of Melbourne, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

⁶A 40 GB Fujitsu drive (model MPG3409AT).