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An asynchronous high-speed synchrotron shutter

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A high-repetition-rate mechanical shutter with asynchronous control and sub-millisecond operation has been developed and tested for specialist X-ray systems in the field of medical diagnostics and radiation therapy. Capacitor-coupled linear voice coil actuators are utilized to achieve opening and closing speeds as fast as 700 µs for an aperture height of 4 mm. The design allows for asynchronous control, permitting slave operation of the shutter, a feature that is distinctly suitable for a number of applications including particle image velocimetry, where high-frame-rate operation must be accurately synchronized and triggered by the image acquisition sequence of the detector or timing device. The design and construction of the shutter also makes it ideal, with simple and limited modifications, for applications requiring larger apertures, in particular wide beams as found in many synchrotron beamlines.

Keywords: high-speed X-ray shutter; PIV; high-speed laser shutter; X-ray imaging; radiation dosage control; asynchronous shuttering.

1. Introduction

X-rays provide high-resolution medical imaging and diagnostic techniques to study biological systems, which are typically optically opaque. The use of synchrotron radiation for biomedical imaging is increasingly common owing to the brilliant, coherent and tunable X-ray beam characteristics that are currently not replicable in a standard laboratory setting. Using synchrotron radiation enables micro-scale artifacts to be seen with great definition (Fouras *et al.*, 2009), owing to collimation and linear polarization of the beam combined with the use of specialized data analysis techniques such as quantitative phase-amplitude retrieval (Paganin *et al.*, 2004; Irvine *et al.*, 2008).

When utilizing synchrotron X-ray sources for the purpose of studying dynamic biological motion, shuttering is required to improve image quality by reducing motion smear, but is essential for dosage control to the sample, as may be required for ethical, preservation and safety measures (Brenner & Hall, 2007; Holton, 2009). Shutters are used to selectively block (attenuate) or allow the transmission of an X-ray beam. Attenuation of the X-ray beams may be provided by two mechanisms, absorption and scattering, denoted by the interaction of the X-ray beams with the attenuating material. Attenuating X-rays through shuttering is more difficult than for other wavelengths such as visible light. This is due to the requirement of the flag, the portion of attenuating material used to block the beam, to have high X-ray attenuation qualities (*e.g.* tungsten or molybdenum). The high densities of these materials greatly reduce the maximum speed at which the flags can travel.

Standard computed tomography (CT) (Kak & Slaney, 1988), and more recent applications, X-ray tomography (Morton *et al.*, 1999) and four-dimensional micro-CT (Badea *et al.*, 2009), are common biomedical imaging techniques. In an X-ray environment these techniques require the shutter to operate at very high speeds in order to capture fine details of transient flow, without smear (Morton *et al.*, 1999). Another imaging technique used widely in the field of engineering is particle image velocimetry (PIV), a well established high-resolution non-intrusive optical method for the instantaneous measurement of fluid velocity. To successfully capture images necessary for PIV using X-ray sources, X-ray PIV (Lee & Kim, 2003; Fouras *et al.*, 2007; Dubsky *et al.*, 2010), the shutter requires asynchronous control from the detector. Furthermore, imaging of physiological motion at both micro- and macro-scale levels requires short exposure times at high frame rates, not possible without correspondingly high brilliance. Synchrotron radiation provides the high brilliance needed to successfully conduct these types of dynamic imaging. With these considerations, an asynchronous high-speed shutter suitable for synchrotron X-ray imaging is presented, and can be seen set up for experimental use at the Australian synchrotron in Fig. 1. It offers the capability of image acquisition with sub-millisecond opening and closing times for X-ray PIV and X-ray tomography, driven by a simple redundant, frictionless electromagnetic mechanism.

2. Background: approaches for shuttering

Shutters are used extensively in optical equipment and laser systems. They fall into a distinct few varieties based on their

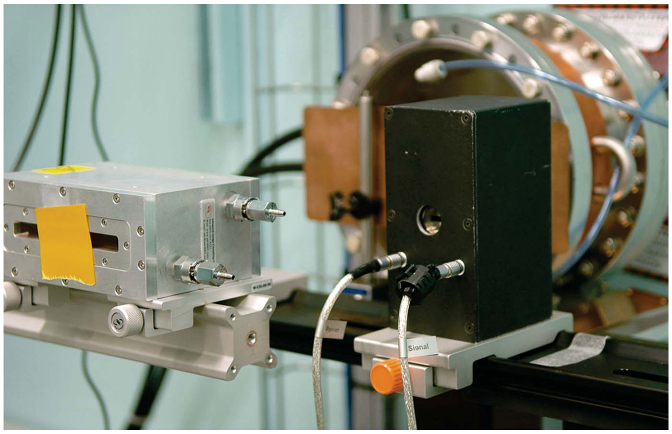

Figure 1
Photograph of the high-speed synchrotron shutter set up for use at the Australian Synchrotron. It is shown mounted onto a horizontal rail, with power and signal leads coming from its front face. The 12 mm × 4 mm aperture is seen as a small slit within the recessed circular opening on the front face.

operation mechanism. Focal plane shutters incorporate either single or multiple curtains, which are placed directly in front of the focal plane, ahead of the photographic film or image sensor. Although these shutters are ideally built into the body of the camera, they suffer from shudder owing to heavy curtains, noise, premature mechanical failure of the moving parts, and distortion of fast-moving subjects. Leaf shutters, that encompass both diaphragm and iris shutters, comprise a mechanism with one or more pivoting metal leaves. They offer high-speed operation and good flash-synchronization with limited image distortion, and are found within many modern point-and-shoot cameras. Rotary disc shutters are semicircular mirrors that rotate in front of a film gate, and are used extensively in the motion picture industry to restrict motion blur between frames.

Through necessity, all of these mechanisms, whether it is translational blade, iris leaf or rotary disc, have been adapted for X-ray imaging and offer different performance outputs based on compromises of functional needs. Although these mechanisms provide effective solutions for visible-light photography, construction of the curtains and leaves out of X-ray attenuating materials generally finds them heavy, slow and prone to friction.

2.1. Commercially available high-speed X-ray shutters

Vincent Associate's Uniblitz line offers an XRS series of shutters specifically designed for X-ray applications with X-ray attenuation rated to 30 keV using a translational blade mechanism. They are currently the only globally marketed commercially available X-ray shutters and are available in three apertures: 6 mm, 14 mm and 25 mm diameter. They operate with total window times (close–open–close) of 9 ms, 35 ms and 30 ms, and maximum operation rates of 50 Hz, 10 Hz and 10 Hz, respectively. Although the XRS series shutters offer a cost-effective off-the-shelf solution suitable for imaging static samples or for general safety purposes, they do not operate at high enough frequencies and do not provide fast enough opening times for PIV imaging sequences that typically involve asynchronous instantaneous frequencies over 300 Hz (to capture an image pair), combined with much lower cycle frequencies, for example 10–30 Hz.

2.2. Rotary wheel choppers

A chopper is the name given to a spinning mechanism that ‘chops’ the light source (in this case X-rays) at a known rate, used as a technique to shutter the beam, similar in concept to those used in old motion picture cameras from the film industry. There are several approaches for the use of choppers with synchrotron sources. As documented by Gembicky *et al.* (2005), these include rotating diffracting crystals or mirrors which scatter the beam, and absorption choppers that use a slotted wheel. These solid metal wheels are attached to a motor and spun at a known rate. The perimeter of the wheel is slotted with apertures that allow the transmission of the beam as each aperture crosses the beam path. Shutters utilizing rotary discs may be aligned with the axes of rotation either parallel, as demonstrated by Cosma *et al.* (1981), or perpendicular to the X-ray beam, such as that presented by LeGrand *et al.* (1989).

Lee *et al.* (2009) as well as Gembicky *et al.* (2005) described high-speed shutters that utilize spinning rotary wheel choppers with apertures slotted around the perimeter. The system presented by Lee *et al.* (2009) was specifically designed to conduct X-ray PIV of opaque flows by having two slits in the spinning lead slotted rotary wheel that was mounted onto a DC motor. The time delay, Δt, between the frames was designated and fixed at three times the exposure.

Gembicky *et al.* (2005) presented an accurate slotted rotary wheel chopper for synchrotron experiments with low jitter. The device operated optimally with an opening time of 2.11 µs, with a fixed 350 µm slot. Their disc was slotted 45 times to provide a range of phase-locking timing options with the synchrotron's storage ring. This requirement is needed for imaging at short microsecond exposures and hence this shutter has a very prescriptive use: small field of view, short exposures and high repetition rates.

Similarly, Cammarata *et al.* (2009) presented a chopper system for time-resolved pump–probe experiments, installed on the ID09B beamline at the European Synchrotron Radiation Facility. The system consists of three parts: a water-cooled heat-load chopper, a high-speed chopper and a millisecond shutter, to allow the isolation of single X-ray pulses, amongst other specialized requirements. The millisecond shutter, a toggling rotating tunnel design, is utilized to lower the pulse frequency on the sample and may be operated asynchronously.

The slotted rotary wheel chopper designs have been successfully implemented at synchrotrons. However, they suffer from numerous drawbacks including very small fields of view, no asynchronous control with the detector, and the necessary manufacture of different slotted rotary wheels if different fields of view or different time lapses between frames are needed. Moreover, Gembicky & Coppens (2007) suggest that the perpendicular orientation is needed to achieve short opening times, whereas the parallel geometry is suited for a high-repetition-rate requirement. Both of these features are necessary when dosage control and high-frame-rate capture are required.

2.3. Voice coil actuator shutters

Linear and rotary voice coil actuators (VCAs) both consist of a coil of wire wound around a bobbin that encases a permanent magnet. When electrical current flows through the coil, an electromagnetic field is induced. The voice coil reacts with this field, causing a proportionate movement of the bobbin and coil (head) either towards or away from the fixed permanent magnet, either on a linear or rotary trajectory. By driving the reverse current through the voice coil, movement is then provided in the reverse direction. Speakers utilize a current (audio) waveform that is input to the driving voice coil to generate movement of the speaker's diaphragm to produce the desired sound. The precise movement has seen VCAs extensively used for high-speed precision linear-displacement systems. By exploiting the electromagnetism of the coils, VCAs can be used effectively in a high-speed shutter.

Maguire *et al.* (2004) constructed a visible-light shutter using the rotary voice coil actuators found from old computer hard-drives. A unipolar supply is fed into a custom-made bidirectional electronic driving circuit that is toggled to achieve movement in both directions. The driver system was updated in 2007 (Scholten, 2007) to feature a single integrated circuit to improve the efficiency, and hence performance speed, over the former circuit. However, if this system were used for X-rays, the extra weight of an attenuating flag would slow the opening and closing times of the shutter, making high frame rates not possible.

3. Twin linear VCA shutter

The present shutter is designed to provide an asynchronous high-speed high-repetition-rate shuttering mechanism for controlling the emission of electromagnetic radiation, particularly X-rays. The design stems from the realisation that simple linear VCAs will allow high shutter speeds from a small displacement. In contrast, owing to their comparatively large rotary displacements, iris-leaf, rotary wheel choppers and rotary VCA shutters do not yield asynchronous control, adequate aperture size and adequate performance for imaging techniques such as X-ray PIV at physiological flow rates through biological models.

3.1. Design and construction

The presented system offers a simple shutter solution with very few moving parts that are lubrication-free, which provides unaffected operation in a vacuum. As seen in Fig. 2, the design consists of two linear VCAs, each operated from separate cores and isolated by an inner housing of low magnetism. The linear VCAs are mounted with vertical travel, one behind the other, and approach from opposing directions within the housing, offering higher closure speeds and greater redundancy, whilst reducing bounce and jitter from cancelling forces.

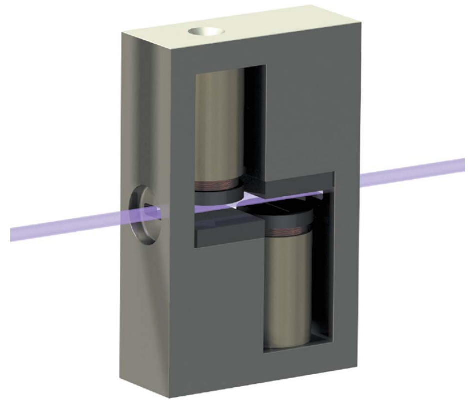

Figure 2
A CAD render of the shutter's inner housing is shown with twin linear VCAs mounted in opposing directions. The coils are shown in the open position, allowing the X-rays to pass through the device denoted by the illuminated beam path. When the closing signal is received, the shutter achieves its sub-millisecond time-to-close, in part, by having the aperture closed from opposite sides simultaneously.

Each linear VCA consists of twin bobbin copper coils attached to the moving aluminium head, which sits around a 5/8 inch-diameter, cylindrical solid-core, rare-earth magnet configuration. The protruding solid upper portion of the aluminium head provides radiation attenuation, particularly good for attenuating soft X-rays. In addition, a 0.3 mm-thick molybdenum insert is slotted within each of the VCA heads and oriented orthogonal to the beam path to maximize X-ray attenuation by blocking out harder X-rays. The combination of the two different density metals at their corresponding thicknesses will effectively block a spectrum of X-rays.

The inner housing chassis is a stainless-steel wire-cut construction, featuring slot apertures in the front and back faces. Two neoprene foam pads form damping end-stops against which the linear VCA heads rest in the shutter's closed position. The inner housing sits within foam isolation mounts in a solid aluminium outer casing. These mounts dampen vibration and reduce any residual motion of the stainless-steel inner housing caused by the rapid halting of the VCA heads at their ends of travel.

The overall rigidity of the device comes from the solid metal inner and outer housings, which have a mass ratio to the two moving VCA heads of 27:1. The heavy mass of the housings reduces movement and provides long-term reliability. Currently the shutter has run 100000+ cycles without failure or need for the replacement of parts. The simplicity of the construction allows easy access for service and replacement.

The shutter may be fixed accurately to a translational stage, as seen in Fig. 1, *via* four mounting bolts. A mounting plate has also been constructed for direct attachment onto a standard optical table. Both options eliminate the need to tediously align the shutter with the beam and sample in the x and y planes, and completely isolates any remaining movement to the foam isolation mounts.

3.2. Operation

Fig. 3 illustrates the main sequence of events involved in the shutter's operation. Drive capacitors are charged under the influence of an electronic controller, such as an LMD 18200 3 A, 55 V H-bridge chip. A timing device coordinates an activation TTL (transistor–transistor logic) signal that instigates the capacitors to dump the stored current across the two linear VCAs in a short time frame. The current generates magnetic fields around the bobbins, which are repelled by the magnetic field developed by the solid-core rare-earth magnet configuration, to provide a high driving force that moves the linear VCA heads away from the magnet configuration at very high velocity, with an average acceleration of $\sim$415*g* and an average blade speed of 4.0 m s^{-1}, in a linear trajectory across the radiation beam. The moving heads are halted by the device's steel inner housing, placing the VCA heads directly in the beam path where they fully attenuate the beam. At this point the shutter is fully closed and remains closed with a 'holding' current of approximately 5% of the peak current (specifically chosen to suit the component ratings of the circuit). In the event of circuit failure, redundancy is achieved through the vertical orientation of the VCAs as one of the VCA heads will sit in the closed position owing to gravity and the absence of an electromagnetic field.

Reversing the current to the coils through the H-bridge provides a driving force in the opposite linear direction, moving the VCA heads back to the fully open position, exposing the beam. At this point the timing device has accurately synchronized the detector to begin acquiring the images.

Linear VCAs have a distinctive force *versus* stroke relationship as represented in Fig. 4. The curved nature of the relationship arises from the inductance of the magnet surrounded by the coils of wire. By exploiting the curve's peak through the mid-stroke region, greater overall acceleration can be achieved by limiting the VCAs total stroke length to this 'optimal operation zone'. This is achieved by choosing a VCA with a longer rated stroke-length than is necessary for the device. The initial displacement of the VCA head is then moved to the lower boundary of the 'optimal operation zone', for instance by a non-magnetic spacer, and the total stroke travel is limited by the design of the housing. The force across the full stroke travel is then maximized, at or near the peak force, to maximize acceleration overall.

The high-speed opening motion is hence dampened at its extreme, not by high-density foam as is the case at the closing end of travel but by a rubber spacer that has the dual function of increasing the initial displacement of the VCA head to an optimal force location, and acting as a damper.

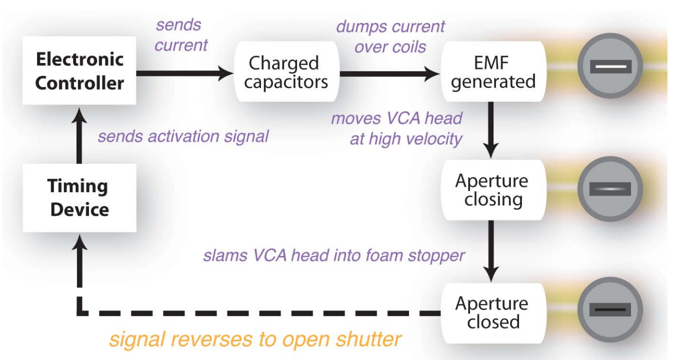

Figure 3
This flow chart details the operating sequence of the high-speed linear VCA shutter. When the initial voltage is applied, the storage capacitors charge. The timing device sends a signal to the electronic controller to dump current through the coils. An electromagnetic field is generated owing to the current in the coil loops that causes the VCA head to be pushed away from the fixed magnet configuration. The electronic controller holds the coil in the closed position by applying a small 'holding' voltage. To open the shutter, the timing device sends another signal which is reversed through the circuitry, now sending current in the opposite direction of the VCA's loops, pulling the VCA heads back towards the rare-earth magnet core. The cycle repeats, triggered by the incoming TTL signal.

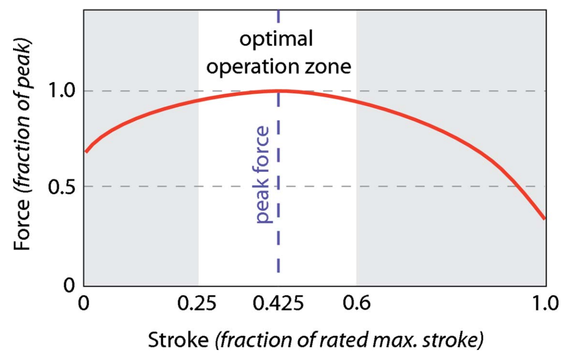

Figure 4
A typical force *versus* stroke plot for linear voice coil actuators showing a bell-shaped profile. It can be seen that there is an optimal operation zone where the central stroke position outputs a larger force than in the lower and upper stroke regions.

4. Experimental results

4.1. Testing of the shutter

During the time-to-open (rise time) and the time-to-close (fall time), the sample receives extraneous doses of X-rays that do not contribute to the image. Excessive or continuous radiation may cause permanent deterioration of the sample, hence minimizing unnessecary dose by shortening the rise time and fall time is crucial.

High-speed photography at 115609 frames s^{-1} was used to test the linear VCA shutter's open, close and jitter parameters. The device was placed between a high-intensity light and a high-speed IDT MotionPro Y6 camera. Three different exposure time signals were sent by the timing device to the shutter and the outputs recorded by the detector. Fig. 5 illustrates the outputs representing the subsequent rise time, fully exposed duration (window time), and fall time of the shutter for each different exposure signal sent.

The plots show smooth operation across all exposures and minimal bounce at the ends of travel. The 15 ms plot represents signal cycles where the capacitor is fully charged at the commencement of open and close. The 3 ms plot represents a

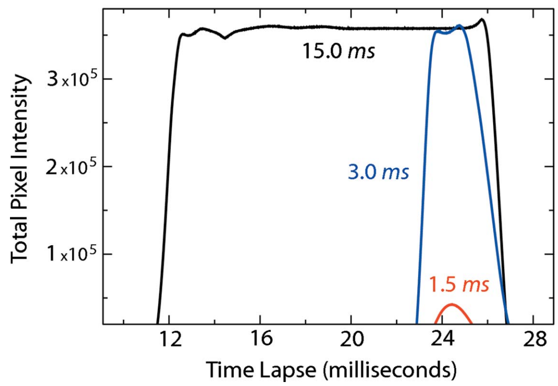

Figure 5
Beam intensity, as seen by the IDT MotionPro Y6's CMOS detector, is plotted against frame number (represented as a time lapse in milliseconds), when three different exposure signals are received. The total pixel intensity depicts the number of pixels which have captured a grey level by the CMOS detector in that particular frame, *i.e.* when the shutter is fully closed all pixels are black and zero grey levels are detected; when the shutter is fully open all pixels are illuminated by some grey level and count towards the total pixel intensity. In this instance the maximum total pixel intensity is ~350000, as governed by the CMOS detector's pixel size and by matching the field of view to the aperture.

shorter exposure signal sent where the maximum pixel intensity is still witnessed from the captured image, *i.e.* the aperture is fully open when the image is acquired. It should be noted that although the image pixel intensity is unaffected, the time-to-close performance has been reduced as seen by the gentler gradient of the fall time. This is caused by the capacitors' inability to fully recharge in the time between dumping the current to open the shutter, and receiving the signal to dump the current to close the shutter. As the input signal becomes smaller the fall-time performance diminishes. The 1.5 ms plot represents the shutter's performance when the duration between open and close signals is much shorter than both the minimum rise time and shorter than the capacitors' ability to fully recharge. When the signal is received to close the shutter, the shutter is only partially open, represented by the reduced peak of total pixel intensity. The shutter then reverses direction to close and the total pixel intensity drops back to zero. Although the peak total pixel intensity is greatly reduced for the 1.5 ms signal, the shutter operates as if drawing back two curtains, and the central horizontal portion of the image will capture pixels at full quality and intensity.

The minimum time-to-open, not including electronic lag from the controller, is represented in the plots as the corresponding rise times of 700 µs to maximum total pixel intensity. This sub-millisecond rise time represents an advantage over other high-speed X-ray shutters, as listed in Table 1.

Very little jitter or bounce is experienced, owing to the frictionless operation and overlapping mechanism of the VCAs.

The shutter provides asynchronous pulsed operation with a minimum window time (fully closed to fully open to fully closed) of 2.8 ms and is fully continuous up to 50 Hz. These values are not limited by the maximum speed of the VCA heads but by the residual EMF generated by the coils at

Table 1
Characteristic summary (performance at maximum speed) of commercially available and recently published high-speed X-ray shutters.

Shutter system	Time-to-open (ms)	Window time (ms)	Aperture size (mm)	Repetition rate (Hz)
UniBlitz XRS6	3.2	9	6∅	50
UniBlitz XRS14	20.0	35	14∅	10
UniBlitz XRS25	10.0	30	25∅	10
Lee *et al.* (2009)†	1.65	3.31	25 slot	5
Gembicky *et al.* (2005)‡	0.0005	0.0021	0.35 slot	22629
Cammarata *et al.* (2009)§	N/A	0.6	0.4 × 0.07	80
Twin linear VCA (current)	0.70	2.8	12¶ × 4	50–350††

† Operating at a maximum rotation speed of 1200 r.p.m. ‡ Operating at a maximum design frequency of 1/12 times APS storage ring frequency. § Operating with the millisecond shutter component of the system. ¶ Width can be increased with no adverse effect on minimum time-to-open. †† Fully continuous to asynchronous pulsed operation.

high frequency. The EMF has a minimum discharge time, preventing fully continuous operation up to the theoretical maximum repetition rate of 360 Hz.

4.2. Characteristics summary

Table 1 details the performance comparison of high-speed X-ray shutters currently found in the literature. The Uniblitz XRS shutters yield reasonable minimum times-to-open for their corresponding aperture widths. The circular nature of their apertures limits the scalability of these shutters, as can be seen by the manufacture of three different sizes and by the increased minimum time-to-open for the larger aperture versions.

The shutters of Lee *et al.* (2009) and Gembicky *et al.* (2005) comprise a spinning disc type (slotted rotary wheel chopper), whereby the imaging system must be synchronized accurately to the shutter. This makes for very complex experimental set-ups that are inflexible with respect to the exposure times and inter-frame ratios. Gembicky *et al.* (2005) has a very small aperture which restricts the field of view, but hence is able to achieve high repetition rates with microsecond minimum time-to-open. However, very high flux is required from the synchrotron source for practical application at this maximum speed. The shutter of Lee *et al.* (2009) has a significantly larger field of view and provides a good minimum time-to-open, but subsequently can only operate at low repetition rate.

The Cammarata *et al.* (2009) system is a sophisticated device, custom-built to isolate single bunches for pump–probe experiments with ultrafast lasers. The asynchronous millisecond shutter component serves to lower the default frequency offered by the other two rotary chopper components. The shutter has a fixed 0.4 mm × 0.07 mm aperture to match the ID09B beamline and, owing to its specific function, only offers a small range of exposures based on the device's tunnel geometry.

The linear VCA system does not suffer from the drawbacks of these designs featuring a scalable field of view with no adverse effects on performance; asynchronous control, which greatly reduces radiation dose to the sample; and simultaneously allows any timing configuration required, with the added flexibility of either being driven by a timing device or a detector. This shutter system has a short minimum time-to-open given the comparative aperture size and yields a modest repetition rate, particularly considering its precise asynchronous nature. It also has the best aperture format for synchrotron light sources, allowing for use with wide beams, and is easily transportable to different synchrotrons and research facilities.

4.3. Twin linear VCA shutter in use at the synchrotron

The shutter has been tested and used for experiments at both SPring-8 (Hyogo, Japan) and the Australian Synchrotron (Melbourne, Australia). The design was optimized for use on the BL20XU beamline at the Biomedical Imaging Center at SPring-8, leading to its 12 mm × 4 mm aperture.

Fig. 6 represents a simplified schematic of the linear VCA shutter in use at a synchrotron, such as on BL20XU at SPring-8. It is placed in the monochromated beam, directly ahead of the sample, and is aligned so that the front and back apertures match accordingly. This is achieved through the mounting holes located at the bottom of the shutter's outer casing, as discussed in §3.1. Alignment in the z plane is performed with a z stage and snapshot photography of the sample until the aperture matches the desired field of view of the sample.

Fig. 7 shows an example of X-ray PIV measurements of blood flow achieved with the use of the linear VCA shutter. The raw phase-contrast images contained clarity with little smear, features that allow the acquisition of data quality needed for PIV analysis (Fouras *et al.*, 2007). Use of the shutter also provides accurate radiation dose control to the sample as the shutter is only triggered to open with the acquisition of an image. If this were not the case, the fluid would heat up, promoting natural convection, and would alter the fluid dynamics exhibited. In the cases where blood and tissue are used, dose reduction is paramount to reduce cell damage and clotting.

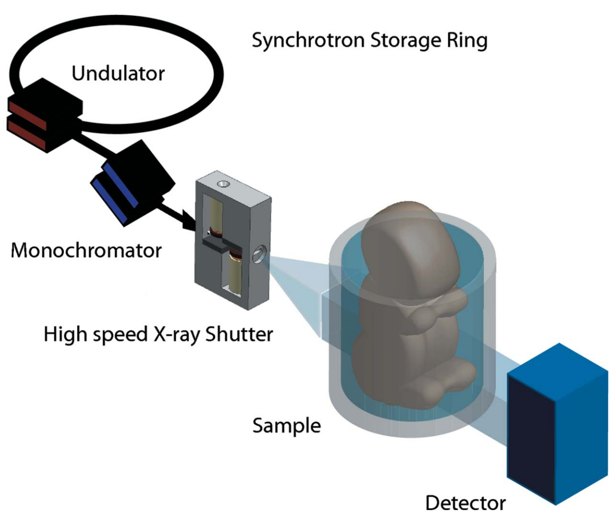

Figure 6
A simplified schematic of the experimental set-up at a synchrotron facility is shown. The broad spectrum that is produced from the undulator is filtered through a monochromator after which a slow shutter would usually be used prior to the experimental hutch. Most commonly with synchrotron experiments, the sample is continually exposed to the beam and the detector captures the data at discrete time points with an onboard electronic shutter. During experiments with biological samples, it is frequently imperative that the sample is exposed to the smallest radiation dose possible. By placing the high-speed linear VCA shutter upstream of the sample, accurate dose control is provided.

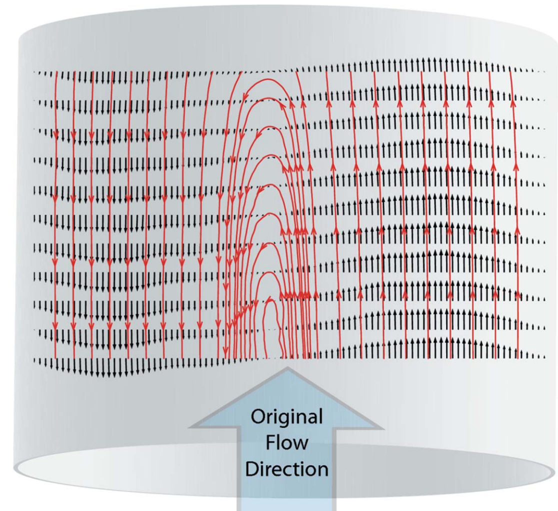

Figure 7
X-ray PIV results showing recirculating blood flow in a glass capillary, captured with the use of the linear VCA shutter. The schematic of the capillary is overlaid with the velocity vector field and streamlines. The recirculation is caused by rapid injection of a bolus of contrast agent immediately before imaging. The experiment was conducted at SPring-8 (Japan) on the BL20XU beamline, and is only possible with reduced dose to the sample to prevent cell damage and clotting. The analysed images were captured at 3 ms exposures, at an instantaneous frame rate of 300 frames s^{-1} for each image pair.

5. Other uses

In the case of high-aspect-ratio beams (used typically with synchrotron X-rays), the linear trajectory of the shutter design provides efficient scaling, by adding more VCAs to increase the width, with no effect on performance.

It should also be appreciated that the twin linear VCA shutter can be used to control the emission of radiation across the entire electromagnetic spectrum. Further to this, the device is not limited to any one application but can be used for industrial and research purposes including medical or industrial imaging using X-rays; biomedical imaging using techniques such as three-dimensional PIV; synchrotron applications, particularly those utilizing narrow or small-diameter high-flux X-ray beams; synchrotron applications utilizing very high aspect ratio (*e.g.* 1:50), laboratory table-top experiments utilizing X-rays or visible light from lasers or lamps; and any experiments or applications which require a high-speed camera with high-rate data acquisition, such as to measure turbulent high-speed flows in working fluids.

The shutter may also provide degrees of attenuation resulting from alterations to the thickness and structure of the VCA head, as may be required for use as a purely safety device. In particular, the thickness and nature of any insert material placed within it can be customized and optimized according to the wavelength nature of the radiation being attenuated. By controlling these features, along with the shutter's timing and synchronization, it is possible to control the degree of attenuation or the intensity of the radiation beam allowed to pass through the device. Overall, the device is easily adaptable to suit various requirements.

6. Conclusions

A simple sub-millisecond mechanical X-ray shutter with asynchronous control and high repetition rate has been demonstrated. To date, the shutter has been optimized for use at the SPring-8 synchrotron's BL20XU beamline in the Biomedical Imaging Center, featuring a 12 mm × 4 mm aperture. It utilizes twin capacitor-coupled linear voice coil actuators to achieve minimum opening and closing times of 700 µs, a complete peak-to-peak cycle in 2.8 ms, with negligible jitter. The shutter has been shown to improve the quality of data acquired for X-ray particle image velocimetry measurements of flow through optically opaque models. This is achieved by preservation of the sample and the sample's flow dynamics through radiation dose reduction, as well as smear reduction of tracer particles in the flow from the ability to use high-frame-rate low-exposure-time image capture. In addition, the shutter is inherently redundant, featuring few moving parts with lubrication-free frictionless bearings, making it well suited for use in a vacuum. It exploits the force–displacement relationship of the linear VCAs to provide optimal acceleration. Furthermore, the design is scalable to accommodate various fields of view with the introduction of different coil configurations. Moreover, the shutter is not only suitable for specialist X-ray systems in the field of medical diagnostics and radiation therapy but can be used to control the emission of radiation across the entire electromagnetic spectrum, rendering it useful for a variety of applications outside of synchrotron imaging.

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