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Optimization of the LCLS Single Pulse Shutter

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Research Advisor: ______________________________

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Table of Contents

ABSTRACT

A mechanical shutter which operates on demand is used to isolate a single pulse from a 120 Hz X-ray source. This is accomplished with a mechanical shutter which is triggered on demand with frequencies ranging from 0 to 10 Hz. The single pulse shutter is an iron blade that oscillates on a pivot in response to a force generated by a pair of pulsed electromagnets (current driven teeter-totter). To isolate an individual pulse from the X-ray beam, the motion of the mechanical shutter should be synchronized in such a way that it allows a single pulse to pass through the aperture and blocks the other incoming pulses. Two consecutive pulses are only ~ 8 ms apart and the shutter is required to complete one full cycle such that no two pulses pass through the opening. Also the opening of the shutter blade needs to be at least 4 mm so that a 1 mm diameter rms Gaussian beam can pass through without modulation. However, the 4 mm opening is difficult to obtain due to blade rebound and oscillation of the blade after colliding with the electromagnet. The purpose of this project is to minimize and/or totally eliminate the rebound of the shutter blade in pursuit of maximizing the aperture while keeping the open window interval $< \sim 12$ ms.

INTRODUCTION

The current single pulse shutter design is an iron blade (ferromagnetic material) onto which a shaft with end bearings is force fitted. The flat blade rocks about the shaft in response to the periodically exerted force by a pair of pulsed electromagnets. Depending on the amount of current flowing through the electromagnets, they magnetize and demagnetize alternately which induces an oscillatory motion of the shutter blade (see Fig. 1).

One face of the blade is exposed to the X-ray beam. This face of the blade is coated with a material which not only absorbs the irradiation coming from the X-ray source but also resists the high peak power from the X-ray beam. To attain this effect the blade is bonded with silicon nitride Si_3N_4 strip.

Definition of terms:

Exposure time t_0: is the time the shutter blade stays open for the FWHM (Full Width at Half Maximum) X-ray beam to pass through. It depends on beam size, beam position, and repetition rate. For this experiment, t_0 is defined at the position where the motion of the blade is steeper (see Fig. 2).

Opening delay t_d: is the time elapsed before the shutter blade responds to an input pulse. It depends on the responsiveness of the shutter blade in addition to the device used to generate the pulse (see Fig. 2).

Static aperture sa: is the difference between maximum and minimum vertical positions of the shutter blade when the pulse picker is not operating (see Fig. 3). It can easily be calculated from the displacement vs. time plot of the shutter by locating the maximum and minimum points on the graph. It can also be measured by taking readings at the respective positions using a laser detector. The laser detector emits a beam (see Fig. 3) and displays the distance between the laser source and the obstacle (in this case the shutter blade). The readings are taken when the shutter blade is fully closed and when it's fully open from the display. The difference between these two readings gives the static aperture sa,

$$sa = z_{\max,s} - z_{\min,s},$$

where $z_{max,s}$ and $z_{min,s}$ are the readings when the shutter is fully closed and fully open respectively while the shutter is not operating (see Fig. 4).

Even if the shutter blade is fully open, the laser beam detects an obstacle because the laser source is positioned vertically above it as can be seen from Fig. 3. The laser source is set up to measure the vertical position of the blade. However, in the actual set up when the pulse picker starts operating in the LCLS, in which case the laser beam is positioned horizontally, the X-ray beam will pass through without any obstacle when the shutter blade is fully open.

Dynamic aperture da: is defined in the same way as static aperture except that the pulse picker is operating when the maximum ($z_{max,d}$) and minimum ($z_{min,d}$) points are located. It's given by the formula,

$$da = z_{\max,d} - z_{\min,d},$$

where $z_{max,d}$ and $z_{min,d}$ are located on the displacement vs. time plot by excluding the oscillation and rebound of the shutter blade as shown in Fig. 4 ($z_{max,d}$ is the trough of the upper oscillation and $z_{min,d}$ is located at the position where exposure time is defined). It's less than the static aperture because of the oscillation and rebound.

Gaussian beam: is a beam whose intensity distribution can be described by a Gaussian function (see Fig. 5).

When fully open, the shutter blade is required to have a 4mm dynamic aperture to effectively transmit the beam without modulation of the wave front. The rms Gaussian beam size σ (rms) that can be transmitted without significant modulation is given by the formula,

$$\sigma(rms) = \frac{da}{4},$$

Where da is the dynamic aperture. For a 4 mm dynamic aperture, σ (rms) = 1 mm.

FWHM (Full Width at Half Maximum): also called Full Duration at Half Maximum is the width of the pulse for which the intensity of the beam is not less than half the maximum value (see Fig. 5). Mathematically, it's given by the formula,

$$FWHM = 2.36 * \sigma(rms),$$

For 1 mm rms Gaussian beam, FWHM = 2.36 mm.

N.B. This calculation shows that a 4 mm dynamic aperture is required to obtain a 1 mm rms Gaussian beam or a 2.36 mm FWHM beam to pass through. However, in actuality the beam won't be as thick as 1 mm. For a 50 μm diameter X-ray beam, only 4*.05 = 0.2 mm aperture is required to avoid significant distortion.

Period τ: is the time between two consecutive pulses (see Fig. 6),

$$\tau = \frac{1}{f},$$

where τ is the period and *f* is the frequency. The frequency of the source of the X-ray beam is 120 Hz. The period is, therefore;

$$\tau = \frac{1}{120} = 8.33 * 10^{-3} s = 8.33 ms.$$

Two consecutive pulses are, therefore, 8.33 ms apart.

Note that not more than one pulse will pass through the aperture as long as the exposure time of the shutter blade is a little less than twice the period, that is $t_0 < 2*8.33 = 16.66$ ms. Theoretically, the exposure time is in the order of *f*s, but to accommodate the uncertainties in timing, it's required to be around ~ 12 ms.

Inclination angle θ: is the angle the shutter blade makes with the horizontal (see Fig. 9).

$$\theta = \tan^{-1}\left(\frac{sa}{L - l}\right),$$

where L is half of the length of the shutter blade and l is the distance of the beam from the tip of the shutter blade.

METHODS AND RESULTS

Although not as effective as anticipated, previously two approaches were employed to address the rebound problem of the shutter blade. The first approach was to damp the vibration created due to the collision between shutter blade and the electromagnet by using a torsion spring. This method resulted in a bigger aperture, but it introduced a new problem: delayed response and longer exposure time. The other problem encountered in implementing this method was the unavailability of enough room underneath the shutter blade to accommodate a torsion spring.

The other approach tried so far is to manufacture the blade from a material that does not rebound as much. Rebounding is not a material property and therefore, such solutions are not easy to come by as experiments should be done to see the response. This approach is still in progress and no result is found up until this report is written.

This research project addresses the bouncing back problem from a different perspective: adjusting the electromagnet in such a way that the blade does not oscillate after colliding with the electromagnet. One of the electromagnets is fixed and so its position can not be altered. However, the other electromagnet can move vertically up and down in addition to tilting sideways from the vertical.

Tilting the electromagnet (bigger inclination angle) increases the aperture (see Fig 7). However, it decreases the exposure time significantly (see Fig 8). This is because, when the inclination angle increases, the shutter blade accelerates more and gains kinetic energy before colliding with the electromagnet. As a result it rebounds with high velocity as soon as it hits the electromagnet (see Fig. 21).This problem can be addressed by slowing down the return motion using a stronger electromagnet or a damper. A stronger electromagnet can exert enough force to slow down the rebound and a damper can absorb the impact energy and reduces the energy available for rebound.

During collision, full contact between the shutter blade and the electromagnet is required to guarantee maximum energy absorption. Full contact is achieved by tilting the electromagnet while moving it up and down vertically. Therefore, all experiments executed in this research are done in such a way that the shutter blade touches the electromagnet fully. Another reason to demand full contact between the two parts is to avoid damage which otherwise will result from single point contact.

<u>Experiments 1 through 6</u>

In pursuit of meeting the requirement of the LCLS (da ~ 4 mm and t_0 ~ 12 ms) six experiments are executed at different positions of the electromagnet without changing the frequency(f = 1 Hz) and the results are summarized in Table 1. The data in Table 1 is plotted to show how the aperture (both static and dynamic) and response time depend on inclination angle (see Fig. 7 and 8). Static aperture increases with inclination angle. So does dynamic aperture.

In experiment 1, $z_{max,s}$ and $z_{min,s}$ are respectively 1.76 and -2.16 mm before setting the shutter blade in motion. Therefore,

$$sa = z_{\max,s} - z_{\min,s} = [1.76 - (-2.16)] * \left(\frac{25.05}{21.75}\right) = 4.6\,mm.$$

The overall shutter blade is 50.1 mm long (L = 25.05 mm) and the laser beam is positioned 3.3 mm from the tip of the blade (l = 3.3 mm). The inclination angle θ (see Fig. 9) is, therefore;

$$\theta = \tan^{-1}\left(\frac{3.92}{25.05 - 3.3}\right) = 10.2^{\circ}$$

The plot for the above set up is shown in Fig. 10 with the screen capture from the oscilloscope shown in Fig. 11. Data points are taken at 50 μs interval.

Reading points from the plot (see Fig. 10);

Dynamic aperture: da = [1.3-(-1.5)] *25.05/21.75= 3.3 mm

Exposure time: t_0 = 755.6 – 749.2 = 6.4 ms

The experimental results obtained from the other experiments (experiments 2 through 6) and similar calculations of da and t_0 are shown in the Tables and Figures along with the corresponding plot and screen capture.

<u>Experiments 7 through 11</u>

Without changing the set up, experiment 6 is repeated for different frequencies of the shutter blade. The data obtained are summarized in Table 2 and the plots are shown in Fig. 12 and 13. As can be seen from the plots, frequency has an insignificant or no effect on both the exposure time and dynamic aperture. The individual plots are very similar to the plot obtained from experiment 6.

DISCUSSION AND CONCLUSIONS

The maximum inclination for which the shutter blade can oscillate is 12.7°. When the inclination exceeds 12.7°, the electromagnet does not exert the enough force to pull the shutter blade back and as a result the shutter blade sticks at one position. A 3.0 mm dynamic aperture is obtained for this set up. This dynamic aperture can be increased significantly (to about 5.0 mm) if the motion of the blade from point 'b' to point 'c' (see Fig. 21) takes longer time. Therefore, this research project boils down to ways of increasing this exposure time without sacrificing the dynamic aperture.

As can be seen from Fig. 25, the shutter starts to open after the input voltage has decreased to 12 from 150 V. This is because of the short life (about 4 ms) of the input voltage. If the duration of this input voltage is longer (about 6 ms) and the 12 V lasts shorter (about 2 ms), the blade moves faster in response to the magnetic force of attraction. This will minimize the time delay t_d and increases the exposure time t_0 meeting the LCLS's requirement of sharper response (see ideal response in Fig. 16). However, the duration of the input volt can not be adjusted manually, and therefore the vendor should be contacted about modifying the product to LCLS's need.

Another way of increasing the exposure time is by decreasing the delay time which requires the use of a stronger electromagnet. When the force exerted by the electromagnet is bigger, the displacement vs. time plot looks like Fig. 14 (a). For smaller force of attraction, the response looks like Fig 14 (b). Therefore, stronger electromagnet guarantee that the motion (referring to Fig. 14) (i) from point 'a' to point 'b' is faster and steeper, (ii) from point ‘b’ to point ‘c’ takes longer time because of a combined effect of reduced delay time and a bigger force which can resist immediate rebound, and (c) from point ‘c’ to point ‘d’ is faster and steeper. Moreover, employing stronger electromagnets reduce the oscillation. This method of solving the problem requires replacing the electromagnet by a bigger one in addition to adding a spacer/washer between the top cover of the pulse picker and the housing to support the bigger aperture. Design modification may not be required if the physical size of the new electromagnet matches with the existing one.

The oscillation of the blade can also be eliminated by employing a damping element (compression spring or a hydraulic damper) between the plate on which the electromagnet rests and the bottom housing of the pulse picker. This method requires design modifications to make a room to accommodate the damping element.

Both exposure time and dynamic aperture remain almost constant when the frequency is varied from 0 to 10 Hz. Therefore, frequency has none or minimal effect on the two parameters t_0 and da.

ACKNOWLEDGEMENT

First and foremost I would like to thank God for he made this possible. This work was supported by the Department of Energy at the Stanford Linear Accelerator Center. I would like to thank the DoE, Office of Science and SLAC for giving me the opportunity to partake in the SULI program. My special thanks go to my mentor David Fritz for his time and mentorship. I would also like to thank Eliazar Ortiz and Marc Campell for their help, and Stephen Rock for his follow up and concern.

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TABLES AND FIGURES

Table 1: Effect of Inclination

Inclination (deg)	Aperture (mm)		Exposure Time (ms)
	Static	Dynamic	
6.7	3.1	1.5	7.3
8.4	3.8	2.4	6.7
10.2	4.6	3.3	6.4
11.3	5.1	2.4	5.8
11.9	5.5	3.0	3.8
12.7	5.8	3.0	3.8

Table 2: Effect of Frequency

Shutter Frequency (Hz)	Exposure Time (ms)	Dynamic Aperture (mm)
1	3.8	3.0
3	4.0	2.7
5	4.0	2.7
7	4.0	2.9
9	4.0	2.9
10	4.0	2.6

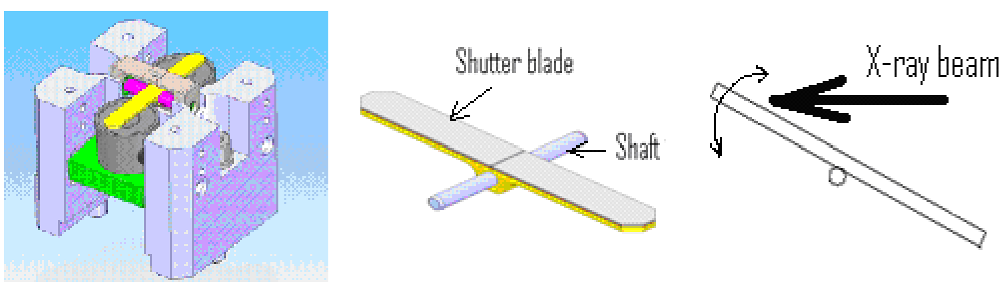

Fig. 1: Pulse Picker

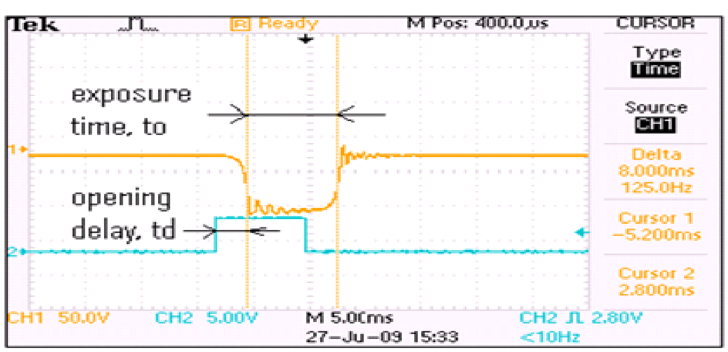

Fig. 2: Response to Input Pulse

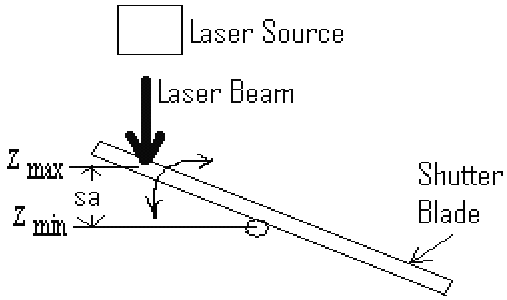

Fig. 3: Vertical Laser Beam

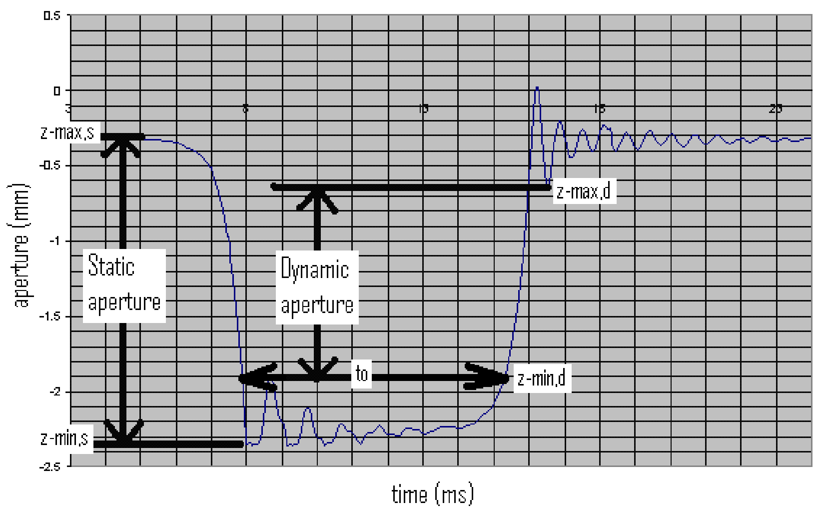

Fig. 4: Static and Dynamic Aperture

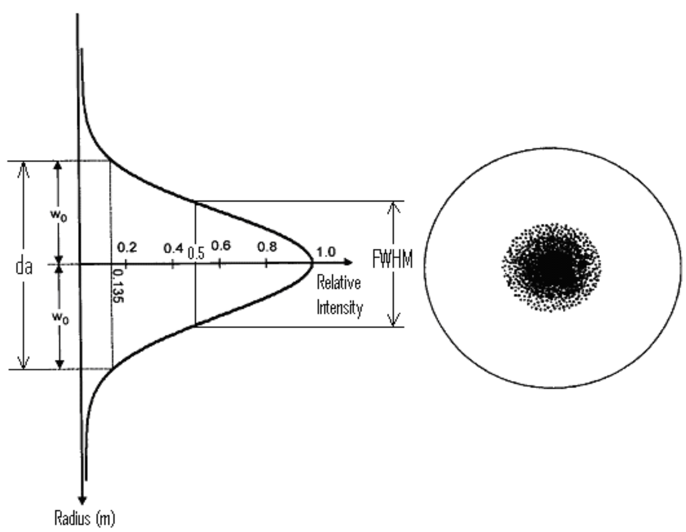

Fig. 5: Gaussian Beam

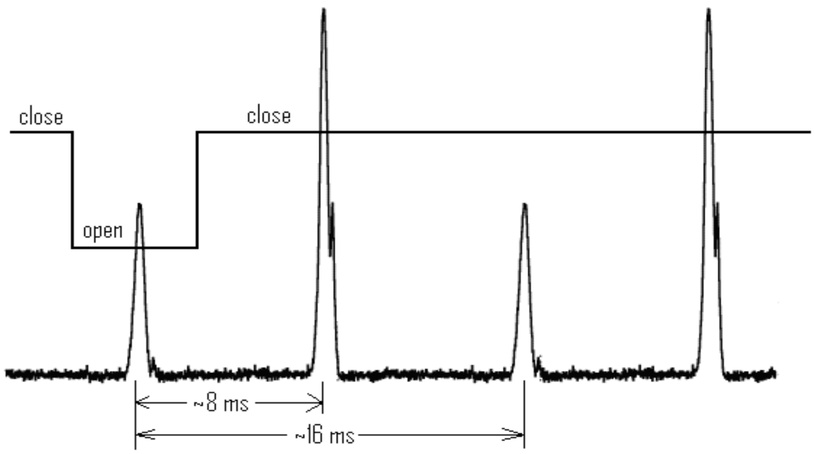

Fig. 6: X-ray Beam Profile

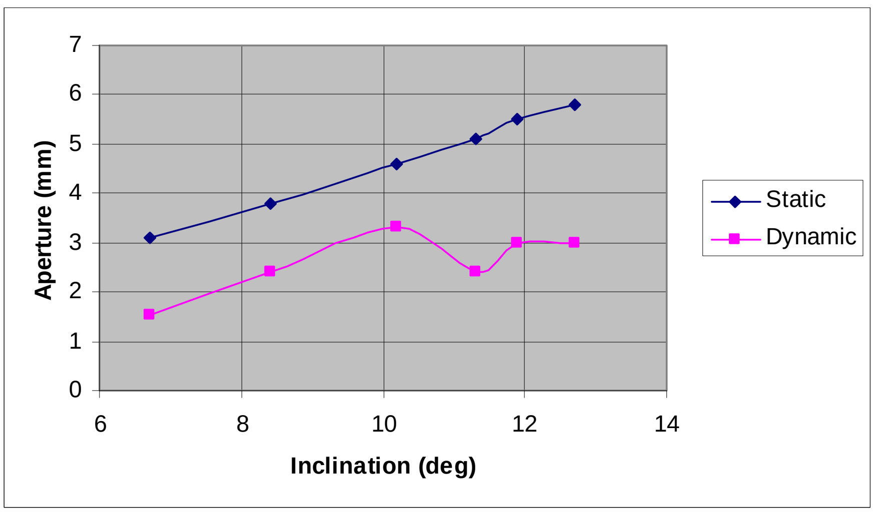

Fig. 7: Aperture vs. Inclination

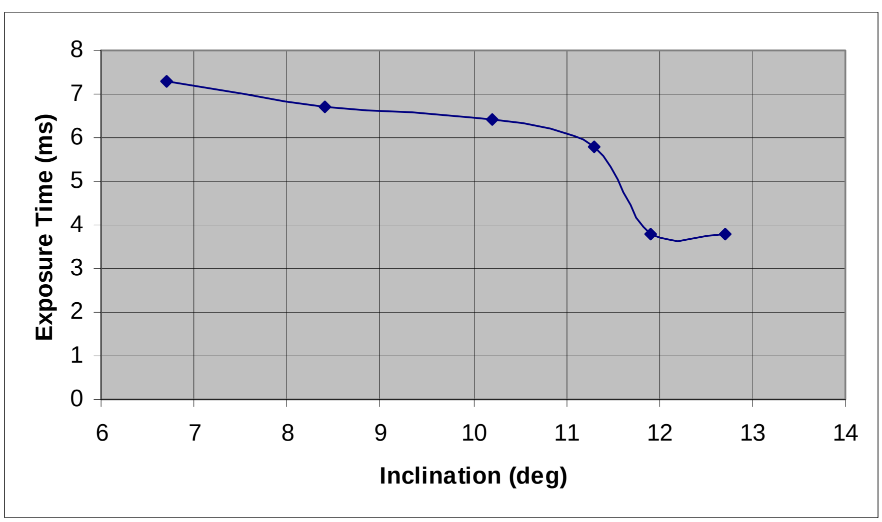

Fig. 8: Exposure Time vs. Inclination

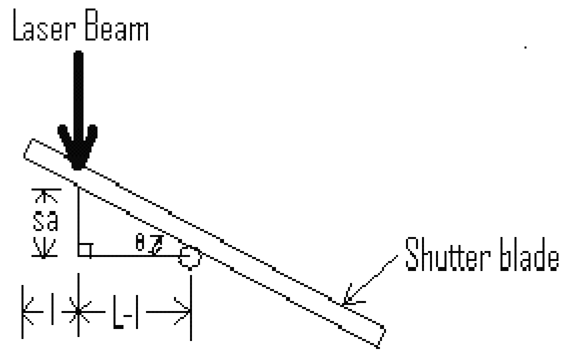

Fig. 9: Quantifying Inclination

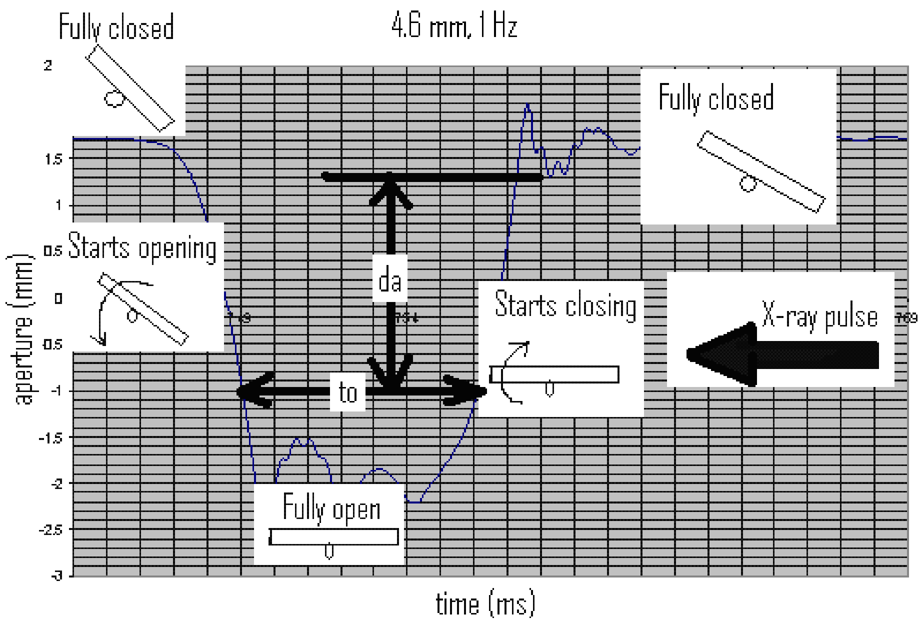

Fig. 10: Aperture vs. Time (experiment 1, 50 μm/s)

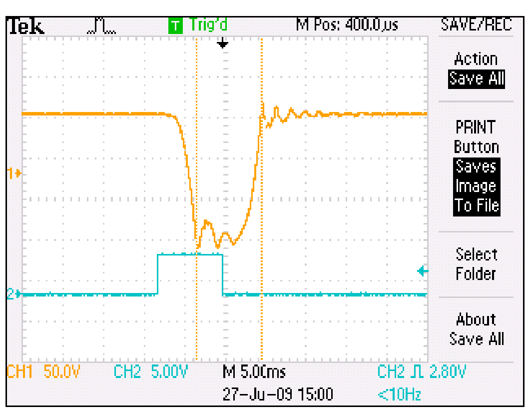

Fig. 11: Oscilloscope Screen Capture (experiment 1)

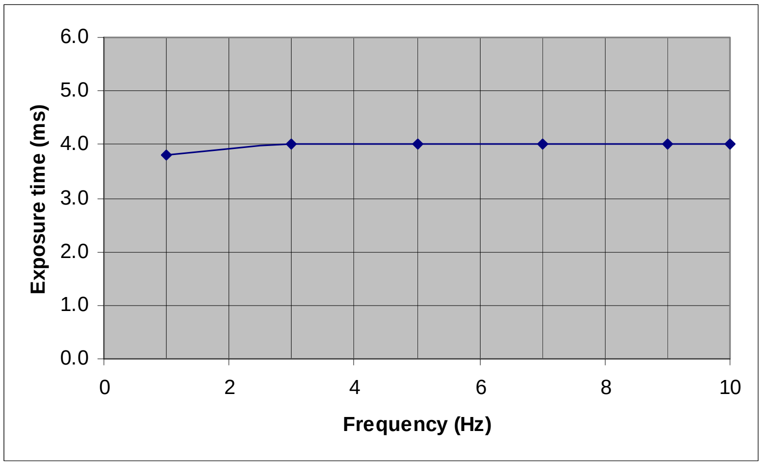

Fig 12: Exposure Time vs. Frequency

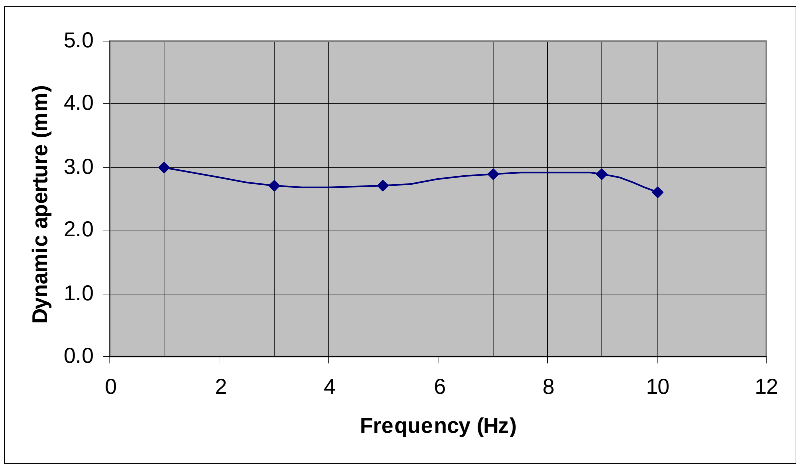

Fig 13: Dynamic Aperture vs. Frequency

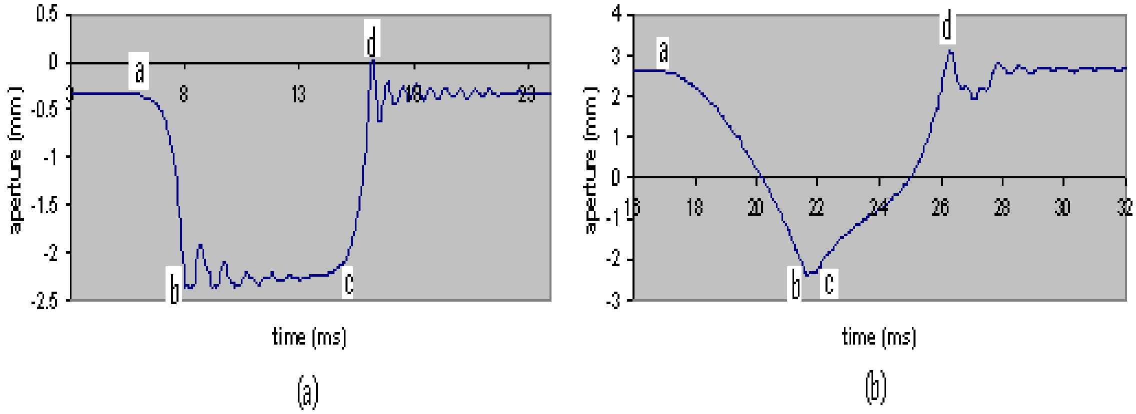

Fig 14: (a) Experiment 2 (2.57 mm, 1 Hz) (b) Experiment 5 (4.90 mm, 1 Hz)

Experiment 2:

$$sa = [-0.33-(-2.24)] *25.05/21.75 = 3.1 \text{ mm}$$

$$\theta = \tan^{-1}\left(\frac{2.57}{25.05-3.3}\right) = 6.7^{\circ}$$

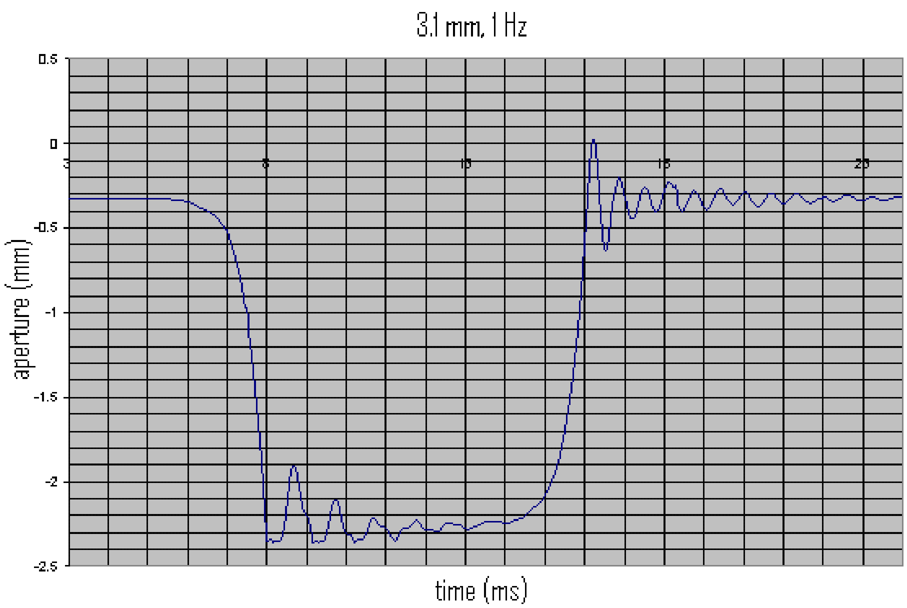

Fig. 15: Aperture vs. Time

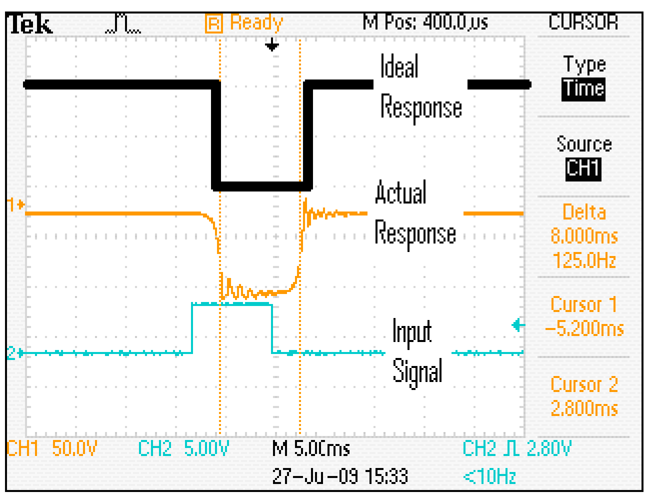

Fig. 16: Oscilloscope Screen Capture and Ideal Response

$$da = [-0.65-(-1.9)] *25.05/21.75 = 1.5 \text{ mm}$$

$$t_0 = 15.2 - 7.9 = 7.3 \text{ ms}$$

Experiment 3:

sa = [0.98-(-2.24)] *25.05/21.75= 3.8 mm

$$\theta = \tan^{-1}\left(\frac{3.22}{25.05-3.3}\right) = 8.4^{\circ}$$

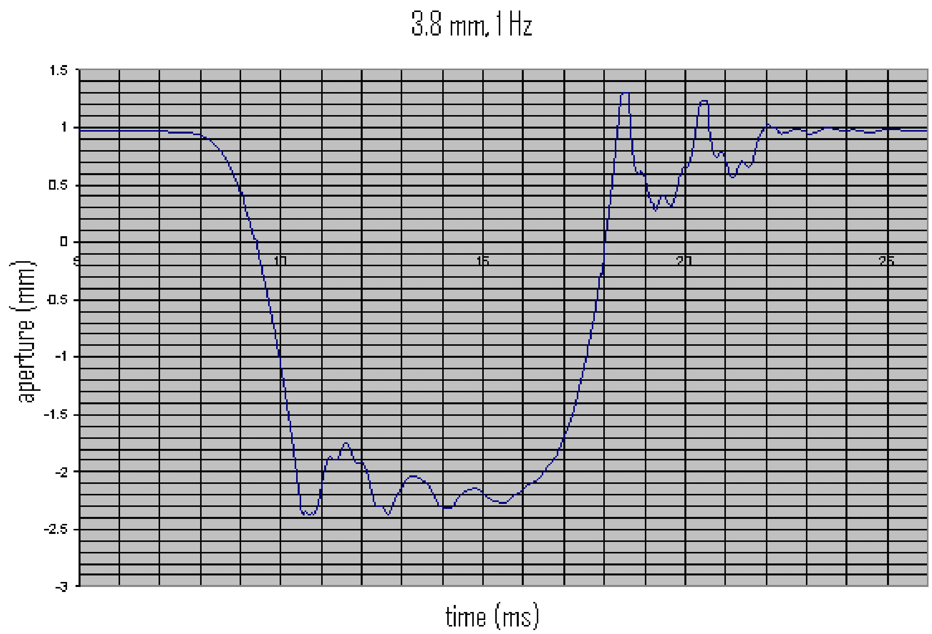

Fig. 17: Aperture vs. Time

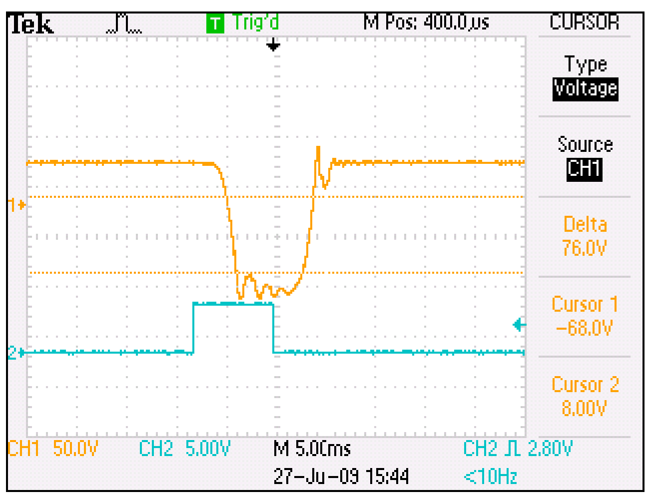

Fig. 18: Oscilloscope Screen Capture

da = [0.25-(-1.75)] *25.05/21.75 = 2.4 mm

t_0 = 16.9 – 10.2 = 6.7 ms

Experiment 4:

$$sa = [2.09-(-2.24)] *25.05/21.75 = 5.1 \text{ mm}$$

$$\theta = \tan^{-1}\left(\frac{4.33}{25.05-3.3}\right) = 11.3^{\circ}$$

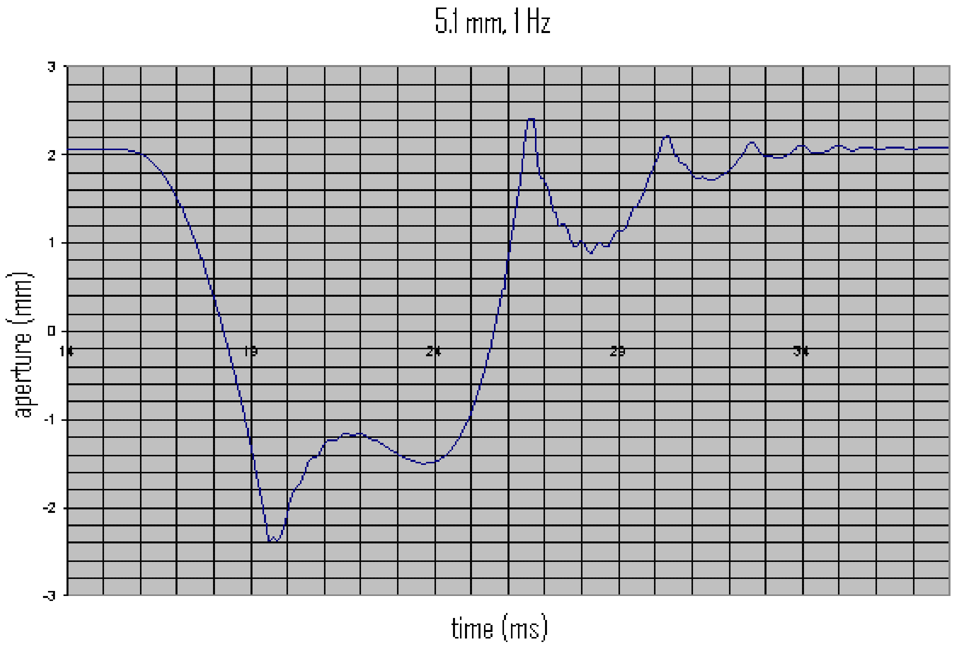

Fig. 19: Aperture vs. Time

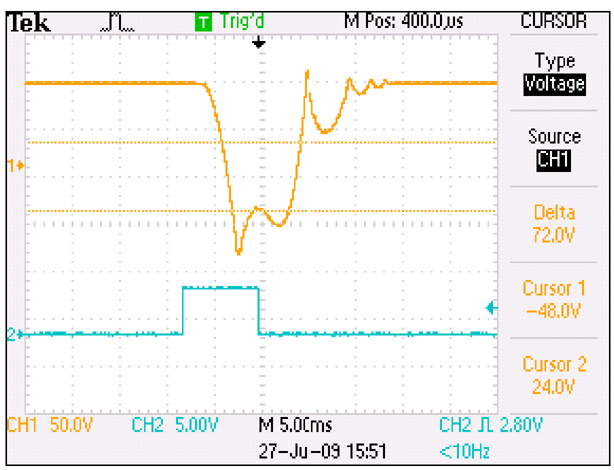

Fig. 20: Oscilloscope Screen Capture

$$da = [0.90-(-1.10)] *25.05/21.75 = 2.4 \text{ mm}$$

$t_0 = 24.7 - 18.9 = 5.8$ ms

Experiment 5:

$$sa = [2.65-(-2.25)] *25.05/21.75 = 5.8 \text{ mm}$$

$$\theta = \tan^{-1}\left(\frac{4.9}{25.05-3.3}\right) = 12.7^{\circ}$$

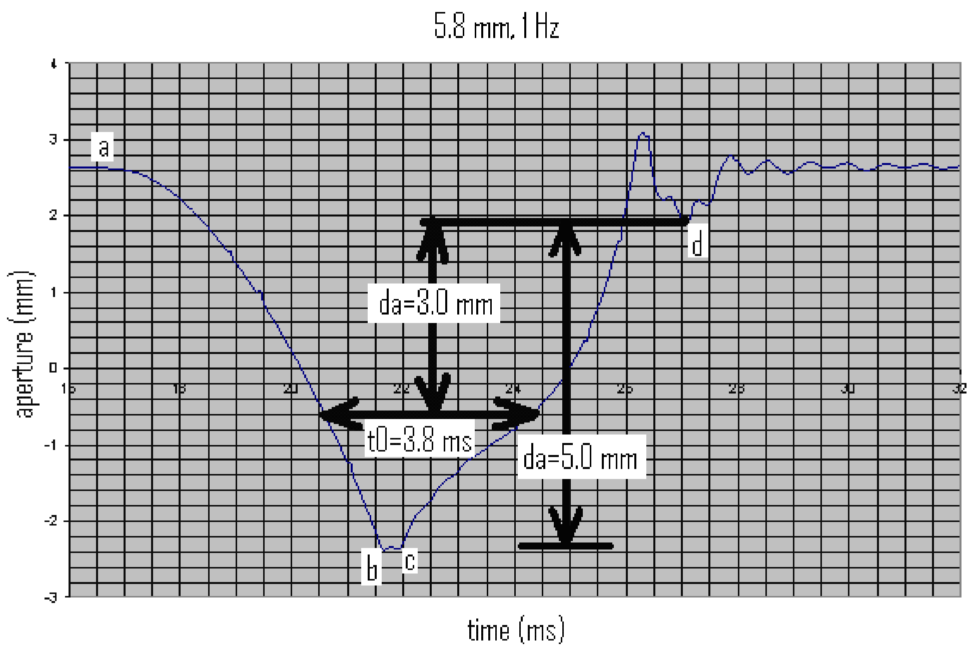

Fig. 21: Aperture vs. Time

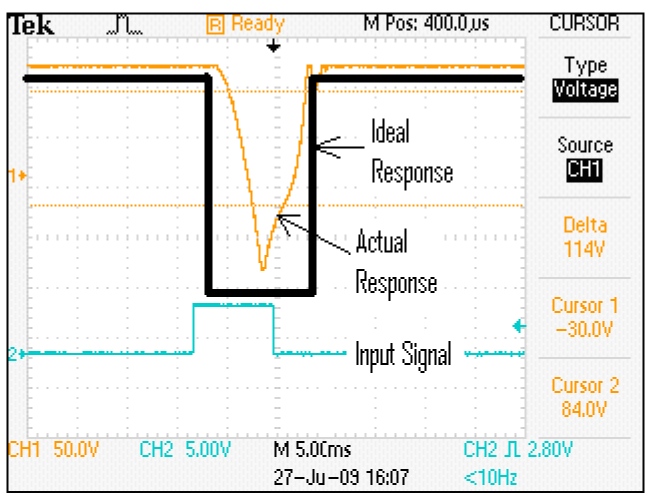

Fig. 22: Oscilloscope Screen Capture and Ideal Response

da = [1.90-(-0.6)] *25.05/21.75 = 3.0 mm

$t_0 = 24.4 - 20.6 = 3.8$ ms

Experiment 6:

$$sa = [2.34-(-2.26)] *25.05/21.75 = 5.5 \text{ mm}$$

$$\theta = \tan^{-1}\left(\frac{4.6}{25.05 - 3.3}\right) = 11.9^{\circ}$$

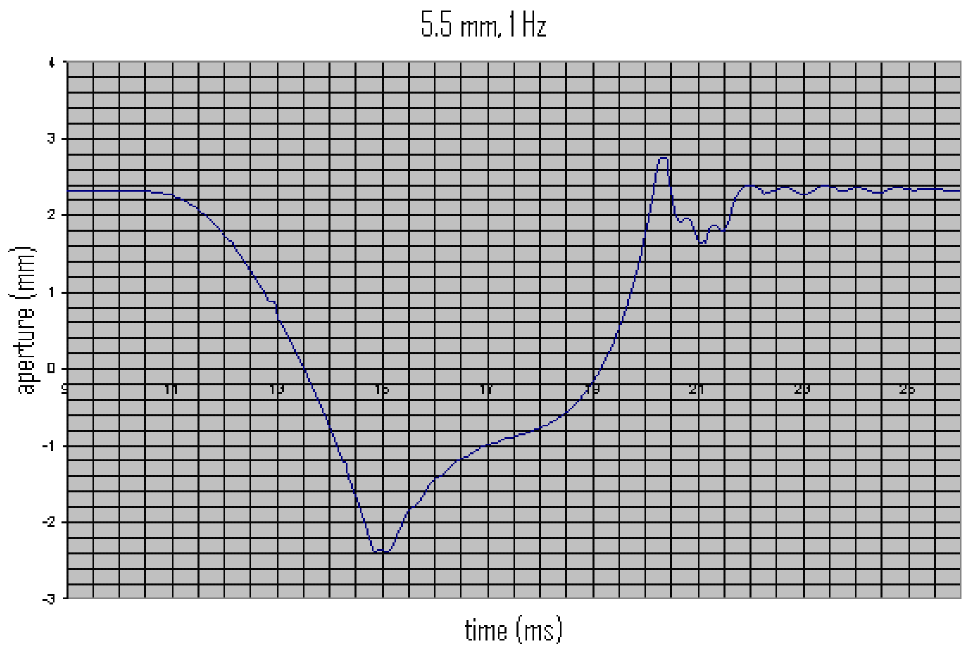

Fig. 23: Aperture vs. Time

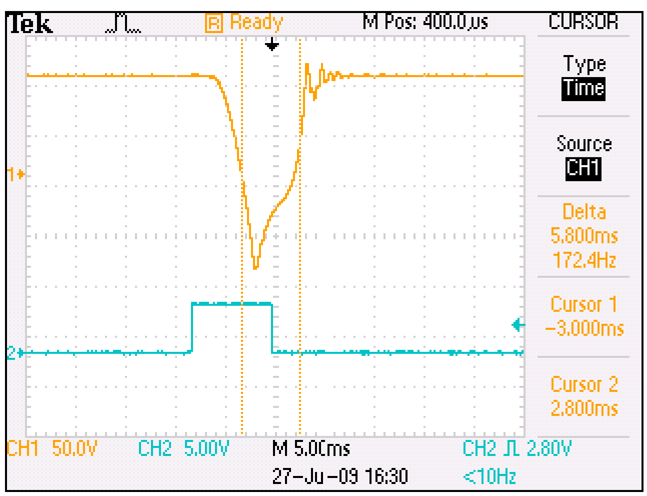

Fig. 24: Oscilloscope Screen Capture

da = [1.65-(-0.8)] *25.05/21.75 = 3.0 mm

t_0 = 18.75 – 13.75 = 3.8 ms

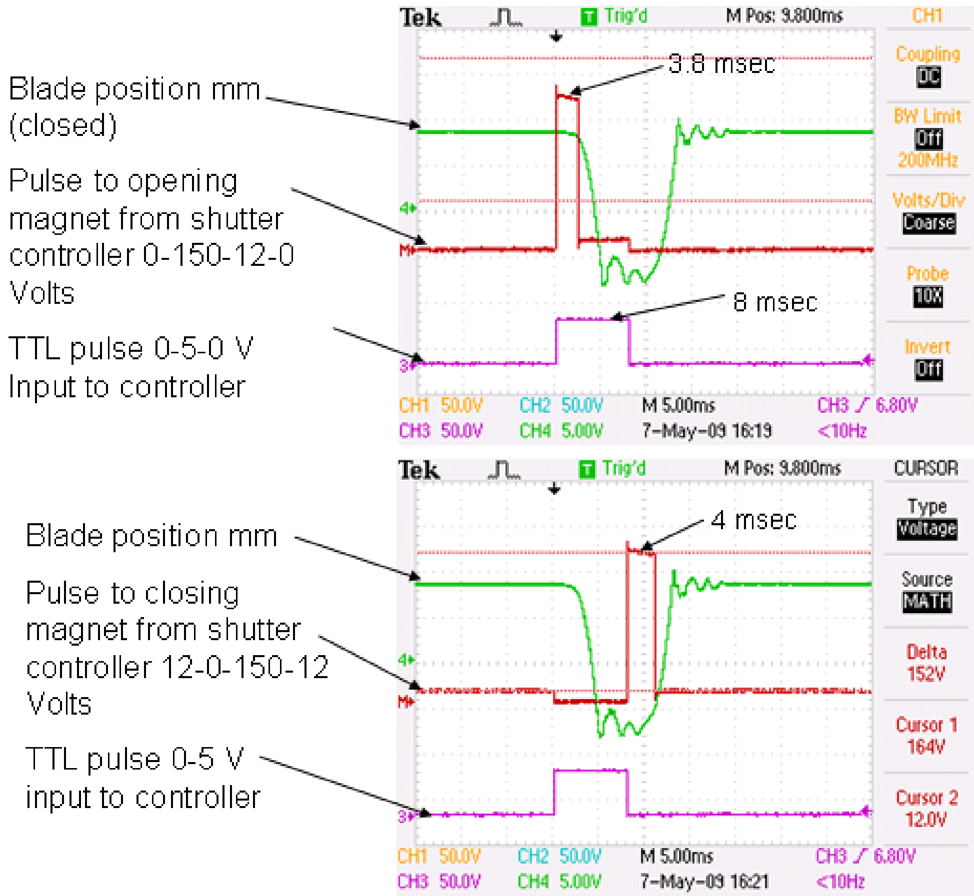

Fig. 25: Input Signal and Response Comparison