Fast Beam Stabilisation of a Large Diameter CW Laser in its Far Field Using 3 inch Piezo Mounted Mirrors

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Introduction

The main drive behind fast beam stabilisation is the desire to spatially lock a beams far field. For large laser systems this can be an ongoing issue which is difficult to overcome. A beams far field may move and drift with time for many reasons, including air currents, thermal expansions and contractions, or possibly unwanted vibrations from the external environment.

To be able to rapidly stabilise a beams far field with great precision is highly desirable since large laser systems require the ability to hit extremely small targets of the order of a few to a few hundred microns. If the pointing is varying substantially the pulse will either miss the target, or will have to be defocussed slightly to ensure direct hits. As a result, the light incident upon a target will be less intense than hoped or anticipated.

This project initially stemmed from the work and technologies used for the HAPPIE Lab project in coherent beam recombination [1, 2] because the general processes required to achieve each are essentially the same. Beam recombination depends upon beam stabilisation in the X, Y and Z axes, meaning locking a beam both spatially and temporally. We decided to first focus on establishing a thorough method to stabilise X and Y and will in the future focus on stabilisation in Z.

Experimental Setup

Changes within the last 12 months have included a new diagnostics setup in order to allow full visualisation of the beam at key points in the system. Within the new diagnostics we now have three far field cameras. One wide far field, which receives both beams, is used to make major alignment easier. The two other far fields are higher magnification and look at each individual arm of the separated beam individually. Attached to each of these magnified far field arrangements is a New Focus Quadcell Photoreceiver. These components provide highly precise positional outputs which feed into the PID control loops setup within the Small Instrumentation Modules (SIM). The SIM is a device which has an empty mainframe in which you can insert a variety of components, in our case PID controllers, voltmeters and filters, although many other measuring or controlling devices can be inserted. They are versatile tools allowing easily customisable setups for measuring and controlling.

The addition of a near field camera within the diagnostics, imaging both beams, allows for a fuller understanding of how the beam travels through the entire system as it is possible to quickly see if there are any problems like clipping or non-uniform intensity distribution.

The other major update within the system is the addition of a vibration damping mount to try to isolate the Physik Instrumente S340 Piezo Tip/Tilt-platform. This change was essential for progress as the platforms rapid vibrations were driving other optical components on the table to vibrate and resonate at a variety of frequencies. This meant that for these frequencies it was difficult to attenuate any vibrations as the resonances would overpower the correcting ability of the closed loop system.

To isolate the platform a set of Thorlabs Sorbothane rubber feet were used. When the feet are loaded with the correct mass they act as broadband passive isolators, greatly reducing vibrations across a large range of frequencies. The optimum mass for the system is 15 kg. This required the design and manufacture of a steel “heavy mount” (**Fig. 1).**

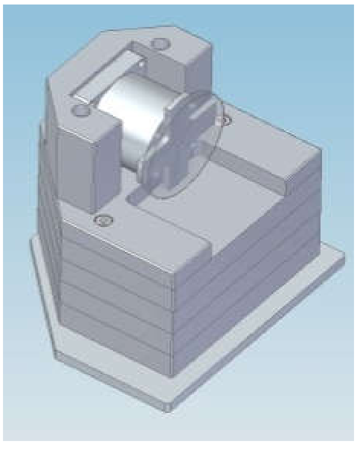

Fig. 1: Vibration damping mount system for the piezo driver and mirror. The mount weighs approximately 15 kg in order to optimise the range of frequencies which the Sorbothane feet isolate.

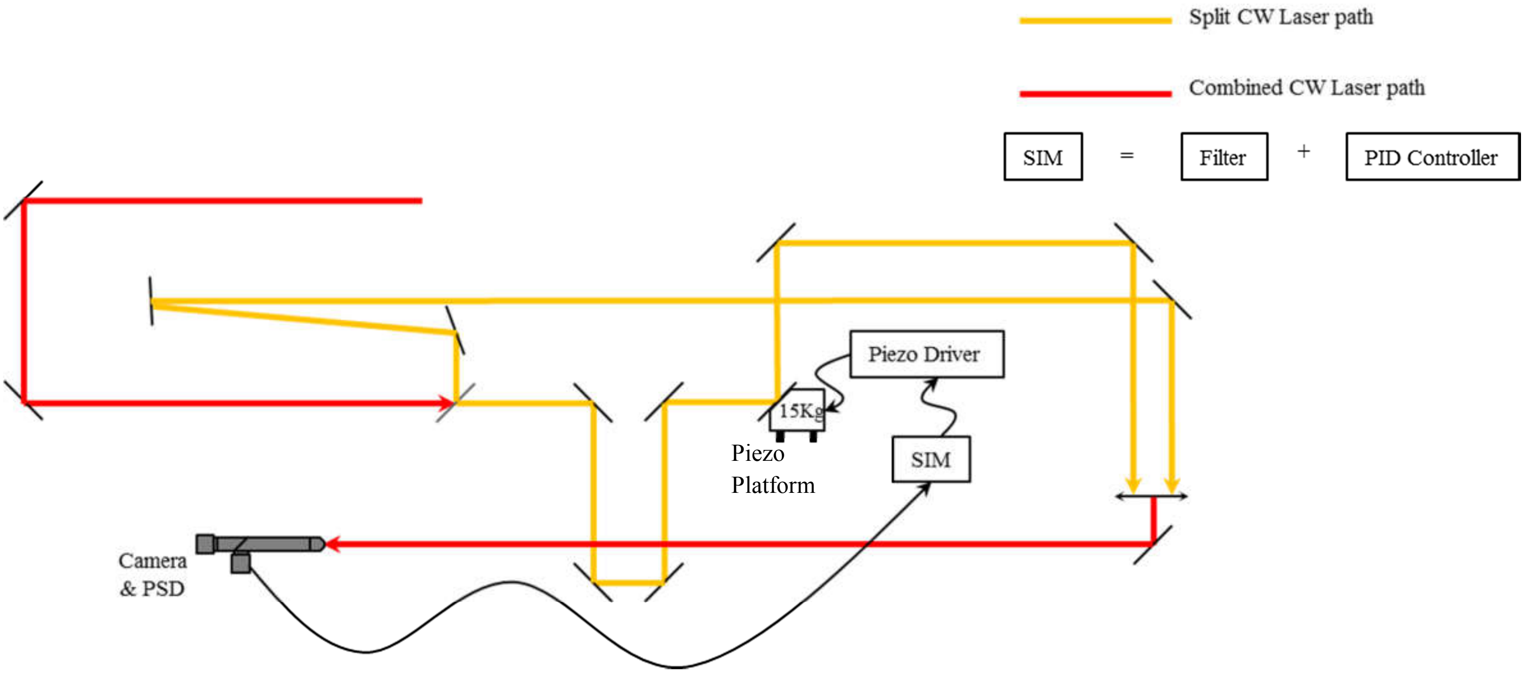

Fig. 2: Schematic setup of the HAPPIE Lab setup used to achieve fast beam stabilisation.

For fast beam stabilisation it was only necessary to use the piezo beamline and one of the magnified far fields (**Fig. 2**). The second beamline will be used when looking into coherent beam recombination and will have a similar permanent piezo setup in the future in order to achieve this long term goal.

Within the setup shown in **Fig. 2** you can see the piezo platform (noted as being mounted on 15 kg). Initial tests were undertaken to try to determine whether rapid stabilisation of a beams pointing could be achieved. In order to do this a set of lightweight mounting cross adaptors was created, upon which thin 3 inch mirrors were glued and then attached to the piezo platform. The tested crosses are as shown in **Fig. 3:**

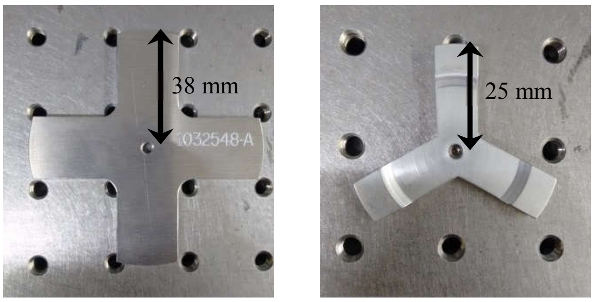

Fig. 3: Left – 4 point cross mounting adaptor.
Right – 3 point cross mounting adaptor.

Mounting Methods

Stabilisation with three different adhesives was attempted; two more rigid types, epoxy resin and superglue, and a third more elastic, silicone. These different adhesive types were tested to see how differing properties would help or hinder attenuation, stability and response of the piezo.

Initial thoughts were that the more elastic adhesive would help to dampen the platforms vibrations thus changing the resonant frequency of the platform and allow a smoother step and reduce the overshoot in the beams pointing. However a few quick tests showed this not to be the case and that the rigid adhesives produced a quicker and more controlled step response.

The adhesive used was not the only variable within the mounting of the mirrors, the cross adaptor was also changeable. Initial thoughts were that the cross used would not have as much of an impact on the step response as the adhesives themselves. However, the 4 pointed cross was only tested once, with the epoxy resin glue; whereas the 3 pointed cross was tested twice, once with silicone glue and again with superglue, therefore it is not clear whether this actually is a valid assumption. It is known that by reducing the total mass mounted upon the front of the piezo platform should lead to an increase of vibrational speed; hence more tests were carried out using the 3 pointed crosses as they are lighter in weight due to their reduced size.

Optimisation

For a closed loop system to work effectively it needs to be optimised for the conditions that it is trying to work within. The optimisation of the system is done by changing certain parameters upon the PID controllers and filters.

Originally the predominant method of optimisation was to follow ordered trial and error. Firstly, setting the cut off frequency of the filter to an arbitrary value and then gradually increasing the PID's gain parameters (P, I & D) from minimum until stability is lost, then reducing till just stable again. The major problem with trial and error was that it proved very difficult to balance the many variables to produce an optimised stable loop.

The second method relied characterising the system in an open loop format and then simulating theoretical closed loops with Excel. The challenging part within this was that the simulations produced here required our input of parameter settings and our interpretation as to how successful the simulated response looked.

The final, most consistent and successful method is to again complete a full open loop scan and then import the data into a Monte Carlo code. The code scans through many possible PID and filter settings trying to optimise the loop to fit pre-determined criteria. It is then possible to take the simulated settings and input them into the PID controller and filter and have an optimised stable loop created quickly and efficiently.

Characterisation

To be able to thoroughly understand how the piezo mounted mirror will behave when in operation it is essential to characterise the whole system. To create a successful open loop several techniques were tested. It was concluded that the best method was to have the setpoint of the PID controller being driven by the output of a lock-in amplifier, which was programmed to output frequencies between 10 and 2500 Hz. It was then possible to measure the positions of the beam falling incident upon the quadcell photoreceiver by directly measuring the X and Y outputs.

Once a full open loop scan is completed inserting the data into the Monte Carlo code optimises the PID and filter settings to give the best possible attenuation of vibrations across all frequencies.

PID Theory

A PID controller is a tool often used in control systems; it works to reduce a measured error to zero. The letters P, I and D stand for Proportional, Integral and Derivative, respectively. These are parameters which the operator can set in order to produce a stable and ideally an optimised feedback loop.

The output of a PID is designed to act in a way such that it is a correcting factor; this arises from the equation below:

$$\text{Output} = P \times \left\{\varepsilon + I\int \varepsilon dt + D\frac{d\varepsilon}{dt}\right\} + \text{Offset},$$

$$\text{Where } \varepsilon = \text{Setpoint} - \text{Measure}$$

Each parameter acts upon ε differently, when tuned correctly this allows for the correction of errors to occur rapidly. The P term creates corrections which are directly proportional to the current value of ε. I creates a correcting factor which is proportional to the integral of all values of ε with time, it effectively looks at all past errors and can produce accurate corrections for slowly changing errors. D is a term which relies on the current rate of change in ε this term is used to predict potential future values of ε and adjusts the output accordingly.

Within the SIM setup there is also a Butterworth filter acting in a low pass mode, the purpose of the filter is to remove unwanted high frequency noise and resonances. This allows the loop to have greater attenuations at lower frequencies and yet remain stable at higher ones.

Once a characterisation is completed it is essential that nothing within the control loop changes when trying to stabilise as it has been found that a variety of factors may affect the loops stability; such as power of the incident laser. This means that things such as clips in the beam or other misalignments can cause a reduction in power and thus reduce the efficiency of the stabilising loop. Other things like how the piezo platform is mounted also play a major role in loop stability, hence the necessity for the "heavy mount" to be in place and correctly assembled.

Results & Discussion

After full characterisation of the piezo mounted mirrors the following settings for the PID and filter were attained as shown in **Tables 1, 2 & 3**.

Table 1: PID and Filter settings for the mirror attached with epoxy resin.

Axis	X	Y
P	0.7	0.3
I	6000	5400
D	0	0
Fc	1000	900
Filter Order	2nd	2nd

Table 2: PID and Filter settings for the mirror attached with silicone.

Axis	X	Y
P	0.3	0.1
I	7200	6000
D	0	0
Fc	1200	1000
Filter Order	2nd	2nd

Table 3: PID and Filter settings for the mirror attached with superglue.

Axis	X	Y
P	11	1.4
I	530	2700
D	$2\text{x}10^{-4}$	$2\text{x}10^{-5}$
Fc	200	450
Filter Order	2nd	2nd

The characterisation and optimisation of the first two mirrors was carried out before the Monte Carlo code was established. At the time, optimisation of these loops was completed using Excel, thus generating the PID settings shown in **Tables 1** & **2**. In trying different settings in Excel it was not possible to create a stable closed loop with a derivative term, hence why in both **Tables 1** & **2** D is shown to be 0.

The third mirrors characterisation was carried after the Monte Carlo code was implemented, enabling many possible stable and optimised PID and filter settings to be produced. As so many possibilities were tested the code is able to produce results with a derivative term that were also stable, as displayed within **Table 3**.

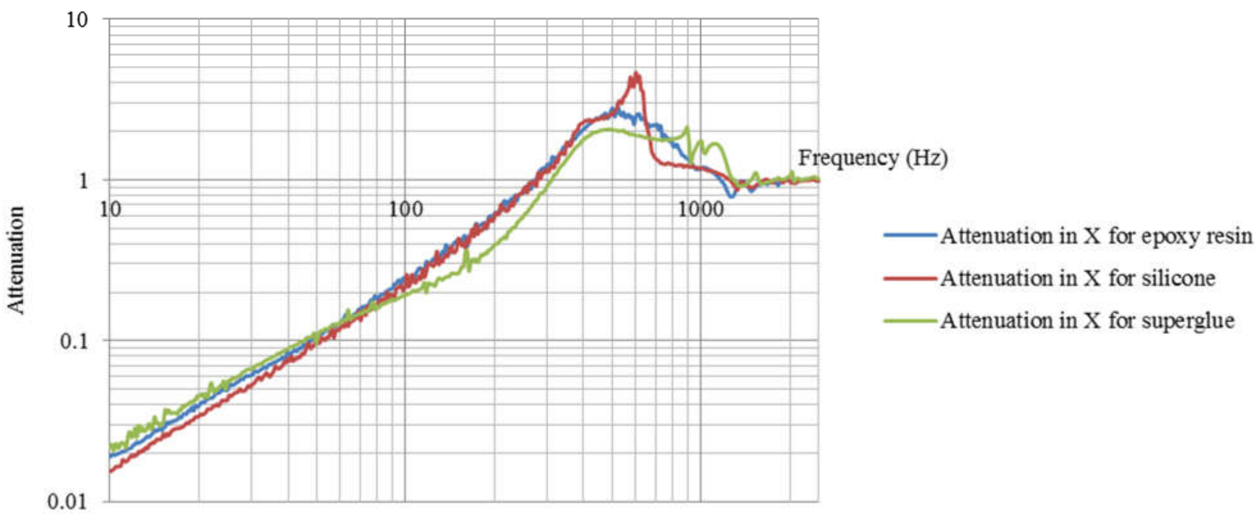

Fig. 4: Attenuation of the far field's vibrations within the X axis for each different mirror across a range of frequencies from 10 Hz up to 2500 Hz.

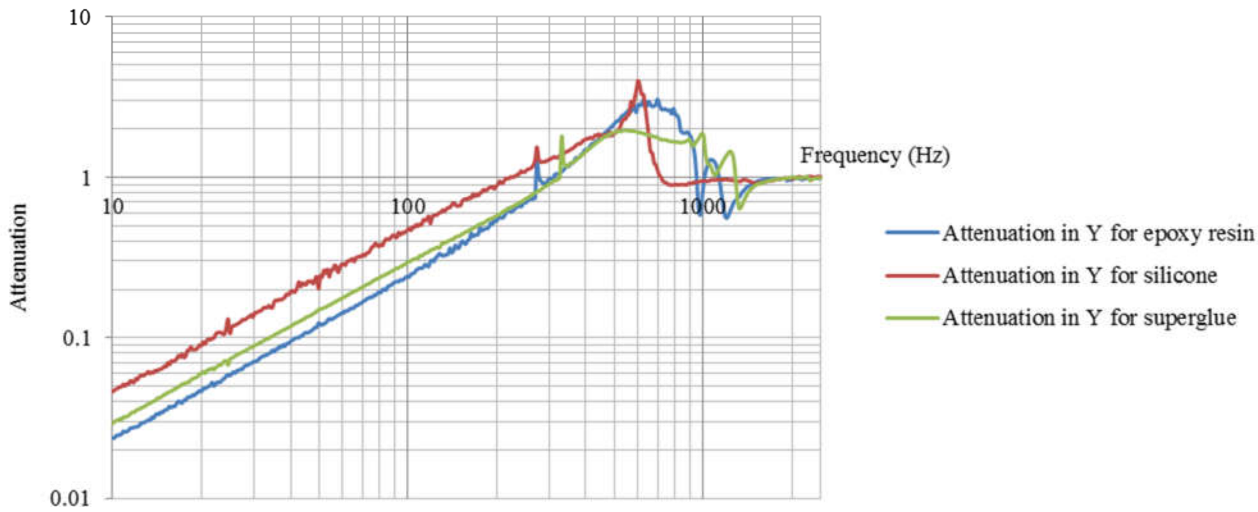

Fig. 5: Attenuation of the far field's vibrations within the Y axis for each different mirror across a range of frequencies from 10 Hz up to 2500 Hz.

Control Loop Attenuations

Figs. 4 & **5** show the measured attenuations of vibrations in the X and Y axes for each mirror. The results are comparable to each other despite the numerous changes made in the mounting methods of each mirror.

As seen in **Figs. 4** & **5** all 3 mirrors displayed reasonable attenuations. The general shape of the characterisation curves showing good levels attenuation at lower frequencies, but amplification arising at higher frequencies, generally the switch from attenuation to amplification occurs at approximately 200-300 Hz.

Attenuations in the X axis

The X axis closed loop characterisations, showing the measured attenuations for each of the mirrors are displayed within **Fig. 4.** It is clear that all the mirrors behave in a similar manner giving similar curves. All mirrors are seen to be capable of attenuating vibrations of 50 Hz by a factor of 10. It can also be seen that at higher frequencies the mirror mounted using silicone experiences a larger amplification with maximum amplification being a factor of 7 at 600 Hz. In comparison, the other mirrors only experience an amplification factor of 4.

Attenuations in the Y axis

The closed loop characterisations within the Y axis for each of the mirrors are displayed within **Fig. 5**. The loop in the Y axis was not able to attenuate vibrations quite as well at lower frequencies than the X axis, achieving an attenuation factor of 10 at a maximum of 40 Hz for the epoxy resin and superglued mirrors and only up to 20 Hz for the mirror attached with silicone. Despite this each of the loops' upper cut off frequency is still seen at 200 Hz as is in X.

Furthermore, the silicone mounted mirror again has, by a smaller margin, the largest amplification factor within the Y axis occurring once more at 600 Hz.

Step Responses

A controllers step response is recorded in order to see how the loop will respond to a sudden 'kick' and how quickly it can regain its stable controlled state. Below are **Figs. 6** & **7,** these show the X and Y axes step responses which again correspond to the stated filter and PID settings within **Tables 1, 2** & **3**.

Rise time and settling time are methods commonly used to describe the speed of a control systems response. Within **Figs. 6** & **7** it is clear that the rise time of all measured step responses are sub ms. The settling time is a little more difficult to determine as it based more on interpretation. For these measurements it is fair to define the settling time by the time it takes the pointing to have small oscillations around the desired value. It is apparent that the mirror attached with epoxy resin has a much faster settling time, settling within approximately 3ms in each axis. The mirror attached with superglue displays a

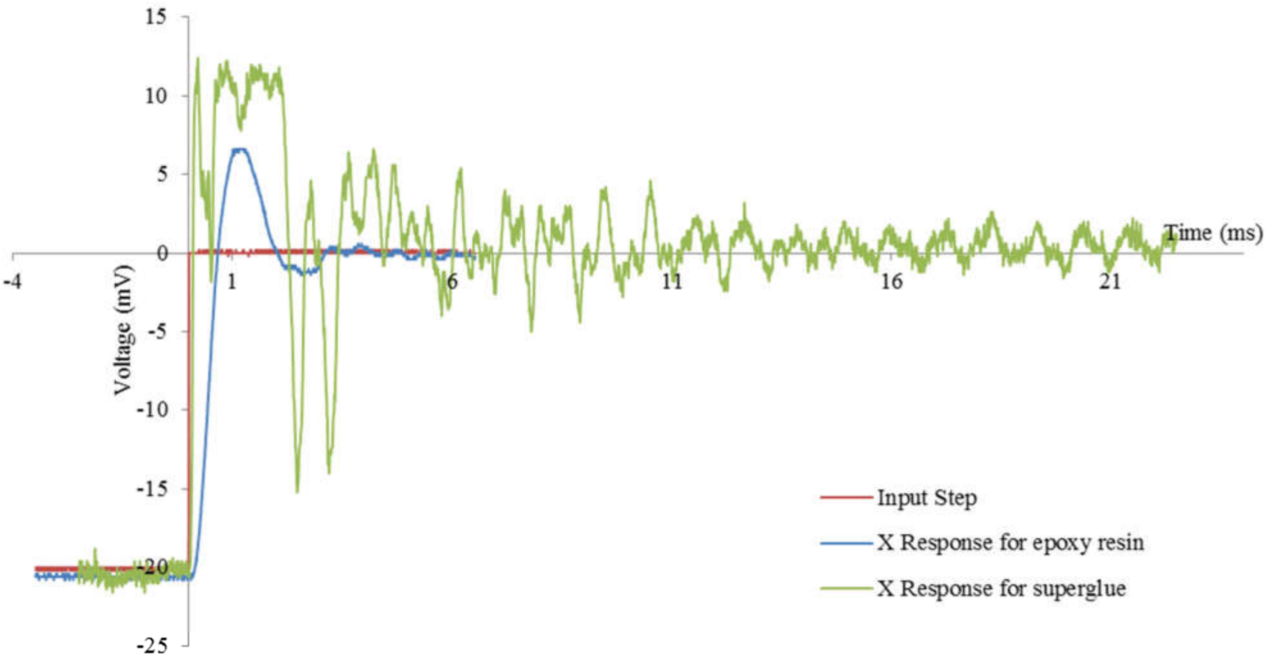

Fig. 6: Response within the X axis of two mirrors when exposed to a square input signal.

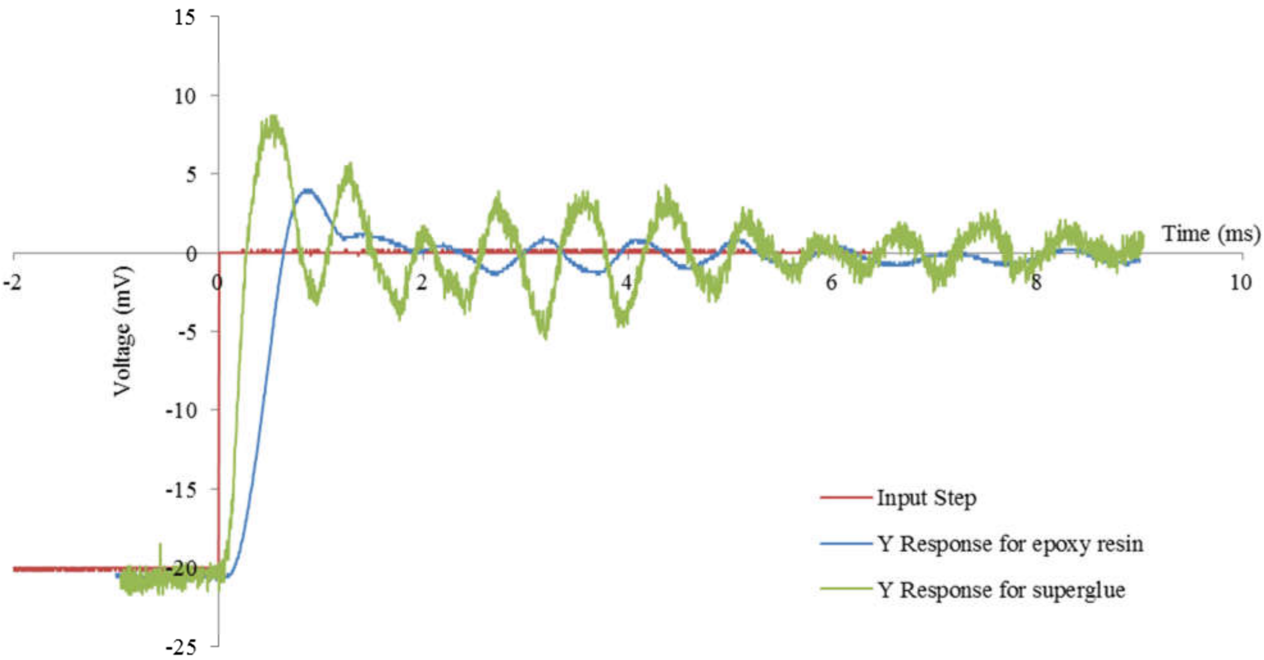

Fig. 7: Response within the Y axis of two mirrors when exposed to a square input signal.

very large overshoot in the X axis thus causing the settling time to be longer, taking more towards 15ms.

It appears that the settling time is more dependent on the mount and adhesive used to fix the mirror rather than which axis it is vibrating in. This is clear to see as the settling time is clearly much smaller for the mirror attached to a four point cross with epoxy resin than a three point with superglue. This can be seen by the fact that there is a much smaller overshoot and therefore the piezo isn't trying to re-rectify as much of a self-induced error. Notice that there are no recorded step responses for the silicone mounted mirror, this is because when testing it showed to be so slow that it was quickly abandoned.

Conclusion

Overall the tests within the HAPPIE Lab have given positive results and show that within small, less complicated systems it is possible to stabilise the far field of a CW laser at a speed of several hundreds of Hz. This was achieved through establishing a scheme where full characterisation followed by thorough optimisation is essential. As the Monte Carlo code is able to simulate the closed loops attenuations for each mirror with great accuracy this makes the whole process very quick and reliable.

To advance upon what has already been established it is essential that further testing is done as several variables changed between one test and the next. For example: the first mirror that was tested was glued using epoxy resin (a rigid glue) onto a 4 pointed cross of 3 inch diameter. However, the following mirror was glued using silicone (an elastic glue) onto a 3 pointed cross of 2 inch diameter.

As so many variables were changed between the tests of the 3 mirrors it is difficult to pinpoint exactly which changes were critical and which were not. The more rigid glues definitely proved to have a slightly better attenuation, and vastly better step response than the silicone glue. For these reasons, it is not necessary to continue further with this type of glue. Between the two rigid glues it is not possible to determine which is best as both have very similar attenuations. Therefore, continuation of tests with either of these glues would be fine.

Taking this project further, tests on larger scale systems have begun. Trials on the Gemini laser have given further positive results, to date it has established that it is possible to stabilise a pulsed laser within a reference path using a CW laser as a reference beam. To fully achieve beam stabilisation a robust scheme needs to be implemented to ensure that delicate components such as the quadcell sensor are shielded from the high power laser shot, while being 'blind' to the motion of the CW beam for the minimum possible duration. This is a difficult task to tackle and the method with which to achieve this can vary depending on the type of experiment taking place.

Acknowledgements

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References

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