Characterisation and correction of actuator hysteresis in astronomical adaptive optics

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Abstract

Adaptive optics is a method of correcting the distortion of astronomical images caused by the Earth's atmosphere. It works by measuring the shape of an incoming wavefront and correcting it by reflecting it off a deformable mirror, which is continuously adjusted to match the distorted wavefront and produce a corrected image. The Durham University Astronomical Instrumentation Group has constructed two adaptive optics systems using deformable mirrors made of a number of segments each positioned using piezoelectric actuators. One problem with this technique is that the actuators suffer from hysteresis, the extension of the actuator depends not only on the applied voltage, but also its previous history. Hysteresis can be corrected using empirical models, however attempts to use this method in adaptive optics systems have so far been unsuccessful as the models lose accuracy as the actuator is repositioned many times. By studying a single actuator I have shown that positioning an actuator using a decaying sine wave voltage can accurately correct the effects of hysteresis. It may be possible to use this method with an empirical model to correct hysteresis in an adaptive optics system.

1. Introduction - Adaptive optics and actuator hysteresis

Adaptive optics (AO) is a method of correcting the distortion of astronomical images caused by the turbulent motion of the atmosphere. When light arrives at the top of the atmosphere from a distant star it consists of as a series of flat wavefronts. However the turbulence in the air it passes through introduces random perturbations in the wavefront, which limits the resolution of ground based telescopes.

Adaptive optics automatically corrects the wavefront aberrations introduced by the atmosphere. It works by measuring the shape of an incoming wavefront and applying corrections to a deformable mirror to cancel the distortions. In practice two mirrors are usually used, a tip-tilt mirror removes the worst distortion, and a small deformable mirror removes the rest. This second mirror could be made from a continuous flexible sheet or a number of individually driven segments.

The Durham University Astronomical Instrumentation Group has constructed two adaptive optics systems using deformable mirrors made up of a number of individual segments, each driven by three piezoelectric actuators. Piezoelectric actuators act as small pistons allowing a mirror to be positioned accurately. One of the problems with their use is that they suffer from hysteresis – the behaviour of the actuator depends not only on the applied voltage, but also the past history of its motion. If the applied voltage is cycled from zero to a maximum value and back to zero, a plot of the actuator extension will show a characteristic ‘S’ curve as shown in figure 1. The maximum displacement of the two curves is typically about 15%.

I have carried out a thorough investigation into various methods of correcting the effects of actuator hysteresis. Hysteresis can be corrected using empirical models that predict the actuator extension, however this method has so far been largely unsuccessful to the limited accuracy of the models and the problem of maintaining accuracy over a long time period. An alternative approach is to position the actuator using a decaying sine wave voltage which converges at a certain value.

The following section explains the various methods used to correct actuator hysteresis. Section 3 outlines my experiment, and section 4 gives the results. Finally the concluding section of this paper explains how actuator hysteresis might be corrected in an adaptive optics system.

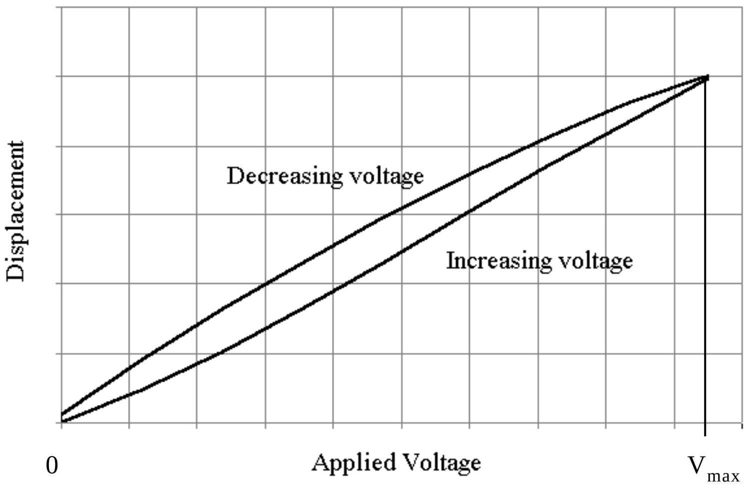

Figure 1. The hysteresis curve for a piezoelectric actuator.

2. Method of correcting actuator hysteresis

The simplest way to control an actuator accurately, is to only move it on the major hysteresis loop. The voltage is increased by moving along the lower curve, and decreased along the upper curve. The approach is satisfactory at slow speeds, however in an AO system, where the actuator is repositioned at up to 1kHz, it does not work. The actuator retains some memory of its previous position and hysteresis is suppressed but not eliminated.

Hysteresis can be avoided by independently measuring the extension of the actuator. This is done in Durham University's ELECTRA project[1], which measures the actuator extension using miniature strain gauges. This technique works well, however it is an expensive option, especially if a large number of actuators are used.

An actuator can be positioned at a known extension by applying a decaying sine wave voltage, converging at a certain value. This is a known technique of positioning an actuator accurately. However it does take a certain length of time to position the actuator, so it cannot be used in an AO system.

Hysteresis can be modelled in several ways. The simplest method is to assume that from a given point within a hysteresis loop, an actuator will always follow the same path, which can be calibrated. A more advanced approach is the Preisach model, which approximates the hysteresis curve to a combination of operators. A detailed description is given by Ge and Jouaneh[2]. Unfortunately previous attempts to correct hysteresis in an AO system using models have been unsuccessful. This is mainly because of the problem of maintaining accuracy over a large number of operations. In the AO system, an actuator is typically repositioned every millisecond.

3. Experimental setup

In order to investigate actuator hysteresis, I built an experiment to measure the extension of a single actuator very accurately. Figure 2 shows the layout of the apparatus. A piezoelectric actuator is used to position a tilting mirror, and the actuator extension is determined by measuring the deflection of a light beam which strikes the mirror. A CCD video camera is used to measure the position of the light beam, and the experiment is controlled using a PC.

In order to measure the actuator extension over its full range of 10µm, and to the greatest possible accuracy; the position of the light beam at the camera had to range over the full width of the CCD – 5mm. This required a total path length from the tilting mirror of 4-5m, therefore the beam was folded using several fixed mirrors.

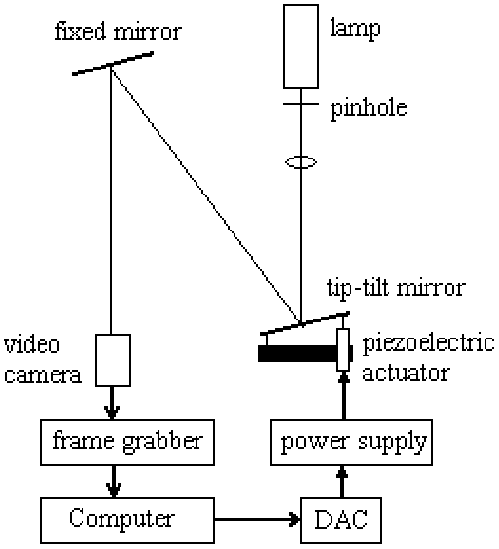

Figure 2. A diagram of the apparatus used to measure the extension of a piezoelectric actuator.

4. Results

4.1 Decaying sine waves

I investigated the effect of applying decaying sine waves to an actuator, by plotting hysteresis loops where the voltage was increased, and then decreased in small steps, and each step value was approached using a decaying sine wave. I studied a range of different decaying waves with different decay times and frequencies; and I concluded that the hysteresis can be reduced to less than 2% by using a wave decaying in 10ms. I found the best wave to use was a linearly decaying sine wave.

Figure 3 shows some typical results for sine waves decaying in 10ms, with different frequencies. It shows that the hysteresis falls slightly as the number of cycles in the decaying waves increases; however for decaying waves with 7 or more cycles, the results are erroneous as the tilting mirror starts to vibrate at a resonant frequency. This represents the maximum frequency of decaying sine wave which can be used with this hardware.

Figure 3 also shows an interesting effect. The hysteresis for decaying waves with a whole number of cycles is greater than that for waves with a non integer number of cycles. Further tests showed that this is not just a coincidence, but I have no explanation to this behaviour. Inverting a decaying wave does not have any effect on the hysteresis, it may a non integer wave has a smoother tail which helps to correct hysteresis.

4.2 Hysteresis models

I investigated the performance of the simple empirical model described in section 2, and the Preisach model. The simple model appears to work very well, it could correct hysteresis to less than 2%, and it could work for 30000 cycles without any sign of losing track.

This last result is surprising, as previous attempts to use this model in an adaptive optics system have shown than it quickly loses track. It is most likely that my result is inaccurate; this may be because I operated the actuator over its full range, whereas in an AO system it would only be used over a much smaller voltage range. Whenever the voltage approaches an extreme value the hysteresis falls to zero, so this could automatically correct any error in the model.

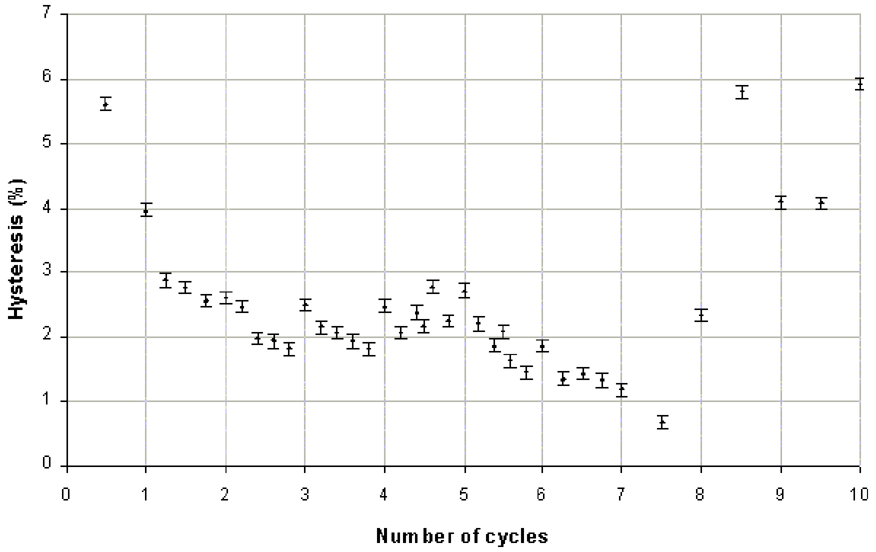

Figure 3. *The maximum hysteresis measured for an actuator positioned using decaying sine waves decaying in 10ms; plotted against the number of cycles in the decaying wave.*

My studies of the Preisach model showed that it does not work very well, the maximum error was over 10%. However these errors only occurred in some circumstances, when the input voltage was increasing and off the major hysteresis loop; in other circumstances the model could predict the extension to 2% accuracy. It is likely that this is due to an error, in either my programming or the model, and another version of the model may be able to work better. Therefore I believe the Preisach model is worth researching further.

5. Conclusions

My research has shown that positioning an actuator using a decaying sine wave voltage converging in 10ms can correct hysteresis to less than 2%. I have also shown that predicting the actuator extension using an empirical model can also correct hysteresis to better than 2%; however previous research has shown that this method cannot be used in an adaptive optics system, where the actuator is repositioned over a small range and at a fast rate.

Although neither of these methods could be used alone to correct hysteresis in an adaptive optics system, it may be possible to use a combination of methods to achieve this. The actuator extension could be predicted using an empirical model for most of the time, and whenever the accuracy of the model deteriorates, the actuator position could be reset by applying a decaying sine wave voltage.

In order to achieve this more research is necessary. Further studies of hysteresis models are needed to determine exactly how quickly they lose accuracy and how this happens. Future researchers could also look at better versions of the Preisach model, as although my results are not encouraging I believe this model does have potential.

Although I have not been able to build a working system, I believe it is possible to correct hysteresis in an adaptive optics system using only software methods. Such a system may be of use in a future low cost adaptive optics project.

References

1. Zadrozny A et Al, 1999. In *ESO/OSA topical meeting on astronomy with adaptive optics*. Ed. Bonachini et Al.
2. Ge P and Jouaneh M, 1995. Precision Engineering – J. Amer. Soc. Precision Engineering. **17**(3) 211-221.