Vibration-compensated interferometer for measuring cryogenic mirrors

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Abstract

An advanced interferometer was built for measuring large mirrors at cryogenic temperatures. This instrument uses active control to compensate the effects of vibration to allow high resolution phase shift interferometry. A digital signal processor and high speed phase control from an electro-optic modulator allow phase measurements at 4000 Hz. These measurements are fed back to a real time servo in the DSP that provides a vibration-corrected phase ramp for the surface measurements taken at video rates. This instrument is planned to be integrated at NASA Marshall Space Flight Center's X-ray Calibration Facility for measuring NGST mirrors at 40 K.

Key Words: Interferometry, Vibration compensation, Optical testing

1. Introduction

Phase Shifting Interferometer(PSI) is frequently used for surface measurements because of its high accuracy and high spatial resolution. The fact that it has to measure sequential frames while controlling phase during a period of time makes it vulnerable to external vibration.
Vibration can cause error in surface measurement and if severe enough will completely wash out fringes. This is particularly true when testing large telescope primary mirrors where it is impossible to put the interferometer and the mirror on the same optical table. In our case, we are going to test a prototype mirror for Next Generation Space Telescope(NGST), which is 2mm thick and 20m radius of curvature, in a cryogenic chamber, the vibration problem can not be circumvented.

There exist a number of ways to reduce the effect of vibration on surface measurement. This paper presents an effective and inexpensive solution to the vibration problem. We use a closed loop phase servo system to actively measure the instantaneous phase, if vibration is detected, then proper correction is made to the phase shift control voltage to compensate for it. In other words, the vibration tends to move the fringes around, what the servo does is to detect the movement when it is still small and then bring the fringes back to where they should be.

2. Method Description

Figure 1 shows a block diagram of the servo. There are two external inputs to the system—the Phase Command input (for surface measurements) and the external vibration that must be compensated.
The servo system consists of 3 components—Phase shifter(with its driver), Photodiode and Digital Signal Processor(or DSP).

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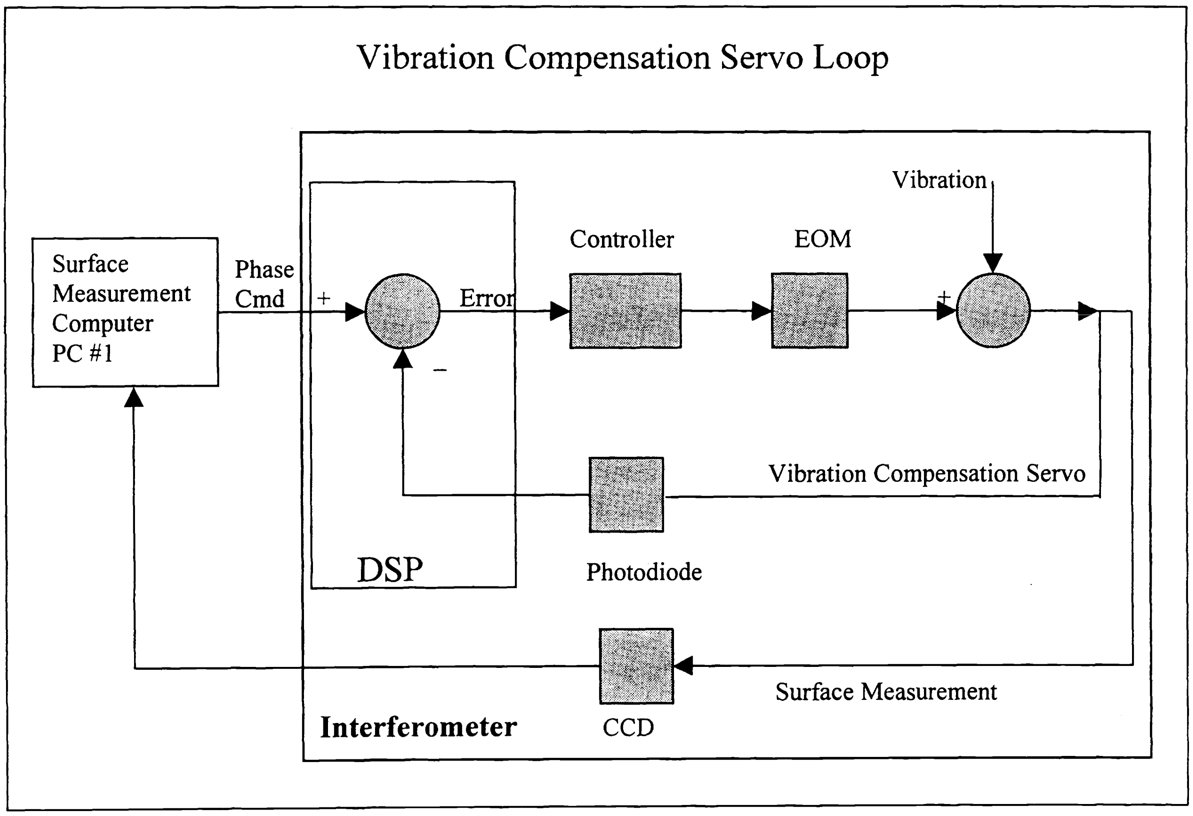

Figure 1. The basic vibration servo is illustrated above. The active element, EOM, makes a correction in response to external inputs (from the surface measurement computer and vibration) to the system.

An essential feature of the method is high frequency phase measurement. The details are shown in Figure 2. The DSP sends out phase shifting control voltage to quickly ramp the phase by 2π during which the intensity variations are measured with the high speed photodiode and digitized. These intensities are fed back to DSP and a five step algorithm is used to determine the instantaneous phase. If a deviation (due to vibration) from the Phase Command is detected, a correction is made to the phase shifting control voltage to compensate for the deviation. Next the phase is held constant followed by a rapid 2π shift in the opposite direction. In this way the system is measuring the phase and then compensating for vibration at a frequency of 4000 Hertz.

The interferometer can be used with any phase measuring software. When a surface measurement is made a phase command for the surface measurement is added to the vibration measurement. Depending on what software you use, a certain algorithm is used to calculate the phase for each point in the detector array. The phase map is then determined and a surface map is generated.

There are two nested phase shifting systems. The high frequency vibration system use phase shifts at a few kilohertz to measure vibration with a single photodiode. The low frequency surface measurement system initiates a ramp and generate surface maps with use of a CCD array. The surface measurement system does not see the high frequency phase shift because the pixel intensities are integrated over many cycles. The high frequency part is just averaged out and only causes a reduction in fringe contrast.

Since high frequency phase measurement is needed to close the servo loop, the phase shifter needs to have rapid response. Glen C. Cole[2] used an Acousto-Optic Modulator(AOM) as phase shifter to build his interferometer with the same vibration compensation device, while we use an Electro-Optic Modulator(EOM) instead. Compared to AOM, using EOM has such advantages as higher light efficiency, much easier alignment, independence on path length difference between reference and test arms.

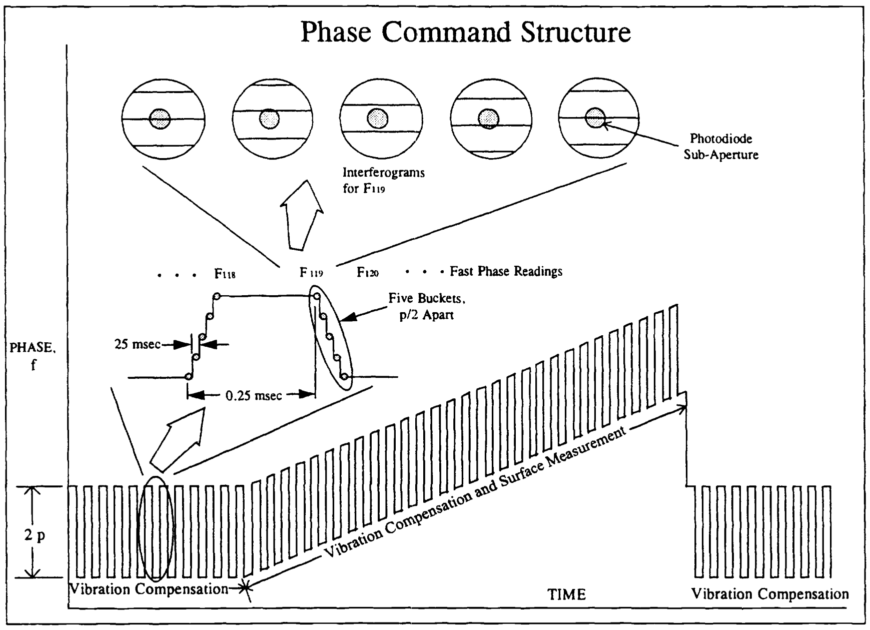

FIGURE 2. The basic phase command structure for the vibration compensation method. The photodiode intensities are used to calculate phase errors at 4000 Hertz. During a surface measurement, a ramp is initiated and an integrating bucket technique is used to calculate a phase map.

Glen Cole and Jim Burge[1,2] characterized the vibration compensation capability of the above mechanism (using AOM as phase shifter) by simulating vibration with a PZT driven mirror. They used a sinusoidal voltage to control PZT, kept the vibration's amplitude at 2 waves and varied the frequency. Figure 3 shows their result. We can see that when amplitude-frequency product is greater than about 300 wave-Hertz, the system can not effectively compensate the vibration.

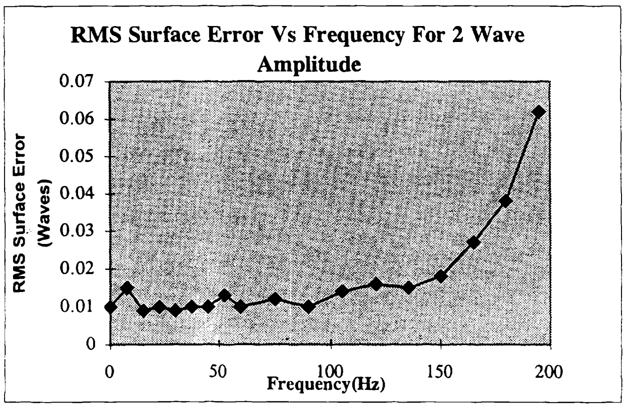

Figure 3. Measured RMS Surface error vs. vibration frequency plot. The amplitude of the vibration is 2 waves. The knee point is around 150 Hertz.

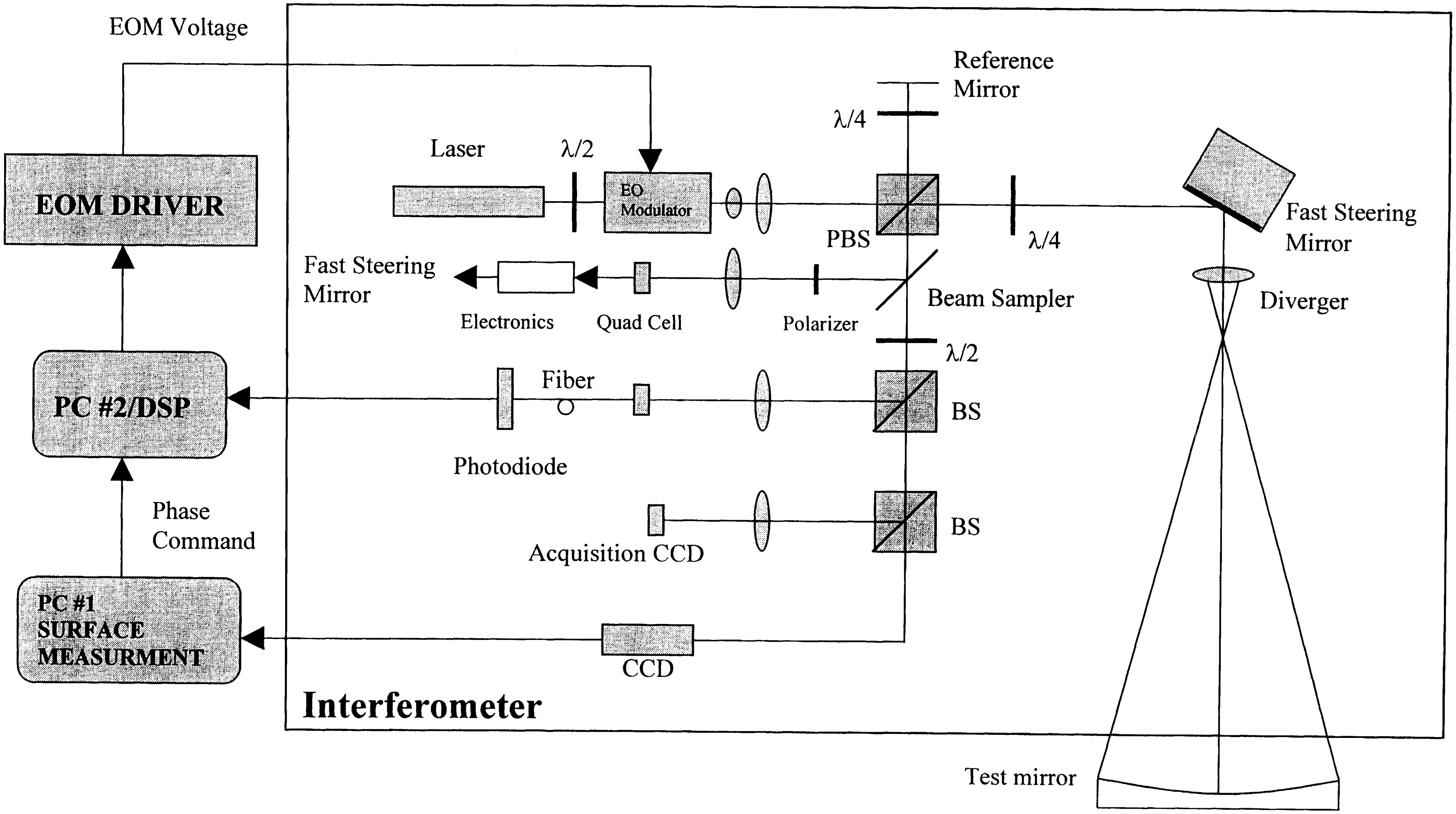

Figure 4. System layout of the vibration-compensated interferometer.

3. The System Layout

This interferometer is basically a Twyman-Green interferometer. Figure 4 shows the layout of the interferometer, the phase servo loop and surface measurement loop are clearly marked. It also shows other features such as the alignment camera and the tip-tilt compensation device to be implemented. The actual picture of the interferometer is shown in Figure 5.

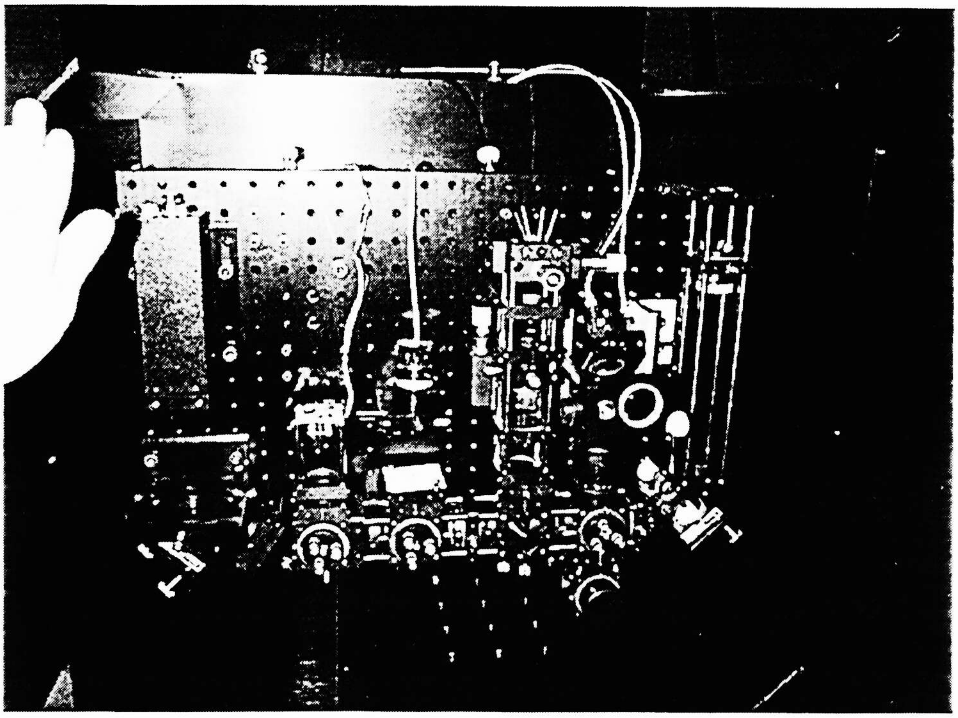

Figure 5. The picture of the interferometer.

4. Electro-Optic Modulator

The key component is an Electro-Optic Modulator, or EOM which serves as the phase shifter. The EOM used in this interferometer is ConOptics 380C which is made of ADP crystal and works on transverse modulation.

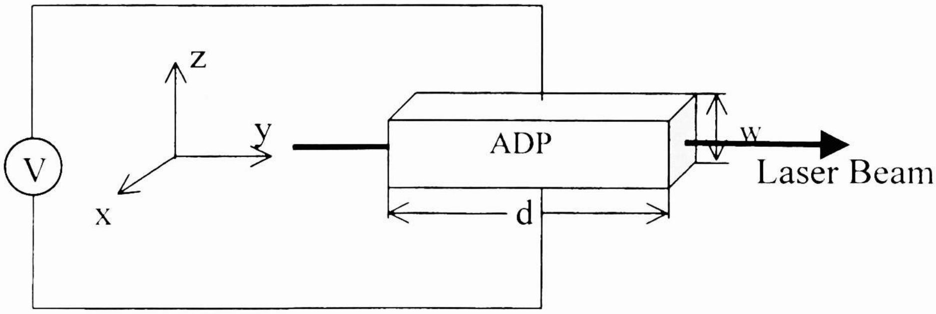

Figure 6. EOM as a Phase Shifter.

When electrical field is applied across the ADP crystal along z-axis,

For x-polarized light, the index of refraction now is:

$$n_x = n_o - \frac{1}{2} n_o^3 p_{63} \frac{V}{W}$$

n_o : refractive index for ordinary light

p_{63} : one element of Pockels coefficients array

For z-polarized light, the index of refraction does't change:

$$n_z = n_e$$

n_e : refractive index for extraordinary light

So, the phase change between the x and z-polarized light due to electrical field[3] is:

$$\begin{aligned} \Delta\Phi &= \Phi_z - \Phi_x \\ &= \frac{2\pi}{\lambda} \frac{1}{2} n_o^3 p_{63} \frac{d}{W} V \end{aligned}$$

For a given EO modulator, the phase modulation is proportional to external voltage *V*. The Voltage which makes $\Delta\Phi=\pi$ is called Half Wave Voltage, denoted as $V_{1/2}$. For ConOptics 380c, $V_{1/2}$=116 volts for 633nm HeNe laser. The EOM driver's output ranges from –400 to +400 volts, which means the phase shift can be up to more than 3 waves.

5. Result

We tested a NGST prototype mirror at Optical Sciences Center, the University of Arizona. The interferometer was mounted on a tower about 20 meters above the mirror under test. The tower is not isolated against vibration and has been set in the past for common path methods such as scatter plate interferometers. With the vibration compensation servo off, we could not get any meaningful surface measurement, while with the servo on, the fringes are much more stable and we can see the servo visibly compensates the vibration. Using the servo, we could readily obtain surface measurements using standard phase shift system running at video frame rates[4]. Figure 7 shows a single phase shifting cycle measurement result. The surface measurement of a mirror can always be improved by averaging multiple measurements.

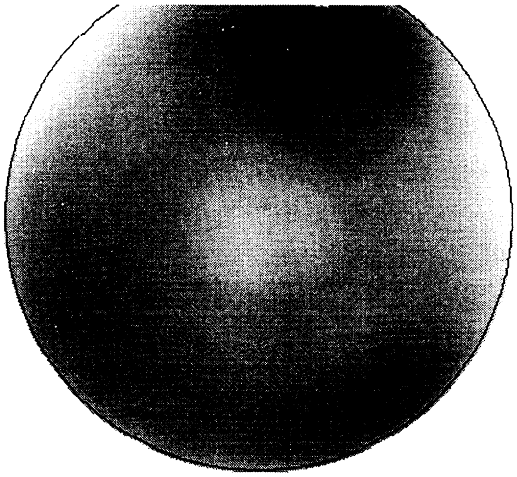

Figure 7. The surface map of NGST prototype mirror (Diameter=2 meters, Radius of Curvature=20 meters). The upper part of it is blocked by a structure. P-V=2.925 microns, RMS=0.4733 microns.

6. Tip-tilt correction

Piston vibration is well compensated by the interferometer. We also integrated tip-tilt compensation mechanism[5] into the interferometer. We already verified that it worked. As of this writing, it is not used in real test yet. Figure 8 shows how tip-tilt can be compensated. A lens focuses the beam onto a quad cell detector, if no tip-tilt is present, the spot would be centered on the quad cell, then no voltage is output from the electronics, the fast steering mirror stays still. If the mirror under test is tip-tilted, the spot on the quad cell will move off the center, then the electronics will out put voltages that are proportional to the spot's top-bottom and left-right deviations from the center, these voltages tip/tilt the fast steering mirror accordingly to bring the spot back to the center. This servo's bandwidth is about 100 Hz.

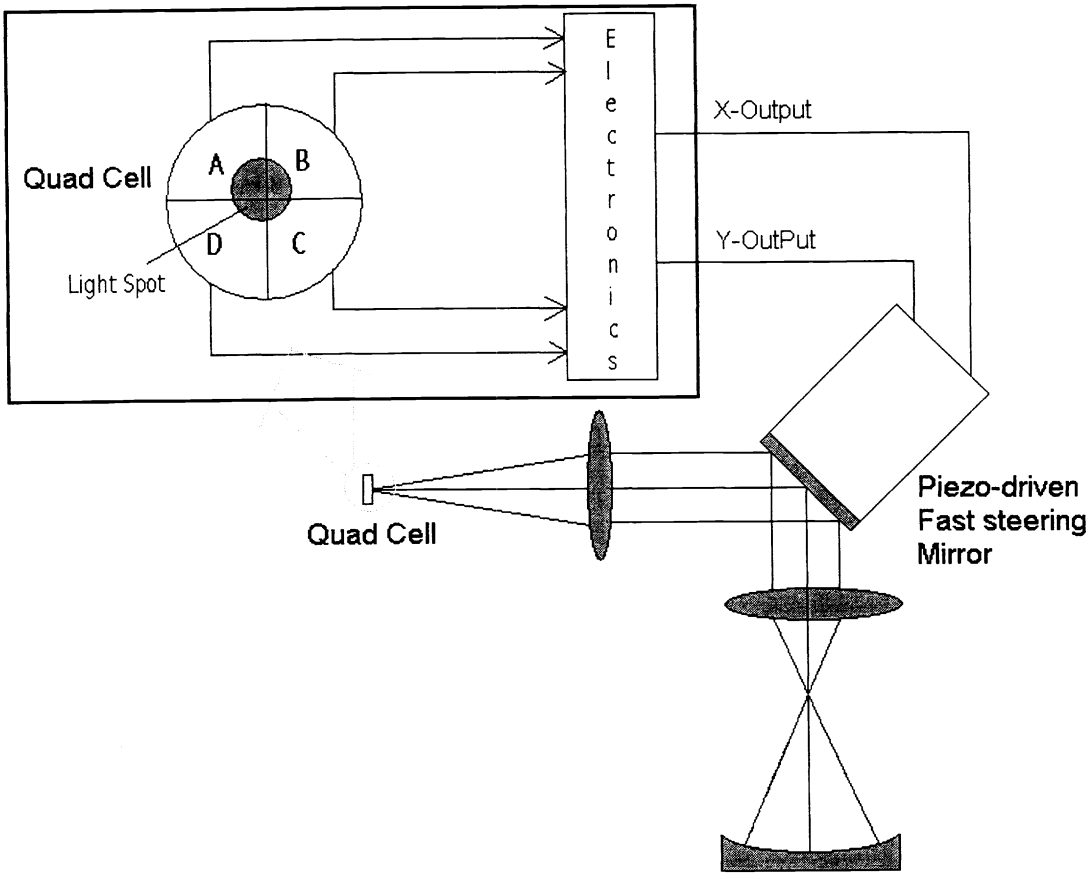

Figure 8. Tip-tilt compensation mechanism. The quad cell is the detector, the fast steering mirror is the active element to do the compensation. The voltages output from the electronics control tip-tilt of the fast steering mirror to do the compensation.

7. Conclusions

The vibration-compensated interferometer was demonstrated to work well. In bad environments, it successfully made surface measurement while other available interferometers could not. In near future when the tip-tilt compensation device works, we will be able to integrate the interferometer at NASA Marshall Space Flight Center's X-ray Calibration Facility to test mirrors at cryogenic temperature.

Acknowledgment

We would like to thank Scott Benjamin who designed all the mechanical parts, therefore made this project successful.

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