Measuring Nanometer Displacements of Piezoelectric Transducers with an Optical Ruler

Physics Individual Project
Siemens-Westinghouse Competition
October 2000

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Abstract

The use of specialized ceramic materials such as Lead Zirconium Titanate (PZT) to control motions on a nanometer scale has heightened greatly in recent years. In this research, the mechanical displacements of PZT samples were measured as a function of applied voltage with the help of a Michelson interferometer.

In accordance with the Piezoelectric Effect, an applied voltage causes the PZT to exert a tiny (typically nanometer) mechanical displacement, or vice versa. The applications of the Piezoelectric effect has reached almost every field of science and technology, being utilized in such advances as the atomic force microscope, any form of vibration suppression, and even the grill lighters used in a barbeque.

The displacement was measured using a Michelson Interferometer – calculating the minute motions using the beams of light from a He-Ne laser (wavelength = 632.8 nm) as a ruler. After calculating the fringe shifts from the Michelson, the displacement factor was discovered to be approximately 316 nanometers for every 500 volts.

How my research topic was selected

My interest in PZTs began in the beginning of my sophomore year, while I was trying to develop a suitable topic for my project that year. Finding a topic that was both feasible, interesting, and current was always the most difficult part of a project. I began scanning through endless editions of various science magazines, searching desperately for the spark of interest that would truly motivate my work for the entire year. When I approached my advisor with this dilemma, he brought up an article about so-called 'Smart Structures' – devices that could detect and repair structural faults on its own. So I began to learn as much as I could about how these structures worked, finding a recurring theme in all of the articles I read – the word 'piezoelectric.' Although I really didn't know what it meant, I remembered using something like it to measure the intensity of sound waves at a Polytec course I had taken the previous summer. The ‘piezo-thingy’ had interested me then, and the fact that it could be used in these new engineering applications just made the device that much more fascinating.

My first brush with interferometry was the following summer, also spent at Polytec, doing research in the Aerospace department. I was working with a Schlieren visualization technique on a new Mach 1.6 nozzle, while one of my friends in the lab was using a Mach-Zehnder interferometer. I honestly found myself envious that he got to ‘play with lasers’ and all I got were a bunch of parabolic mirrors.

When I approached my current mentor last year with questions involving feedback loops and PZTs, he suggested that I think about interferometry. Knowing what I knew from my friend’s paper the previous year, I eventually put two and two together, and came up with this idea.

1 Introduction

With the current rise of nanotechnology and the ever increasing need for precise motion control in nearly every field of science and engineering, special ceramic materials with piezoelectric properties have grown tremendously in importance. These materials are referred to as PZTs, which is an abbreviation for both 'piezotransducer' and the most commonly used type of ceramic material, lead (plumbum) zirconium titanate.

PZTs have the capacity to sense structural faults in bridges, signs of failure on airplane wings, and monitor the integrity of skyscrapers. With these sensory systems integrated into a feedback loop along with piezoelectric actuators, the structures actually gain the ability to repair themselves (Hogan)(Amato)(Williams). Recently, PZTs have even been constructed into gossamer 30 micrometer thick fibers, to allow more efficient embedded smart structures (Wu).

In science applications, the PZT has led to the development of new cutting edge instruments that can actually measure surface topography on a scale from angstroms to 100 microns, counteracting minor variables such as fluctuations in the Earth's atmosphere, in a device called the Atomic Force Micropscope (AFM).

The goal of this research was to measure the displacement factors of a selection of PZT samples obtained from the company Physike Instrumente at voltages up to 1000 V. The 'optical ruler' is a Michelson interferometer, with the PZT mounted to the moveable mirror. The shifts in the interference rings as a function of applied voltage are recorded with a photodetector and used to calculate the displacements.

2 Piezoelectric Effect

The Piezoelectric Effect was discovered in 1880 by Pierre and Jacques Curie, as the property of certain crystals to generate an electrical charge when placed under mechanical pressures (Kistler 1). Likewise, when the PZT receives an applied voltage it produces a tiny displacement. Although most natural materials, such as quartz, and tourmaline, etc, respond to this effect, the response is to such a small degree that the applications with these materials are limited. Ferroelectric materials and polycrystalline ceramic materials such as Barium Titanate (BT) and Lead Zirconium Titanate (PZT), magnify this effect to a usable standard. This is partially because of the isotropic structure of the materials. The centro-symmetric structure of a molecule of Lead Zirconium Titanate can be seen in Figure 1 below (PI 4_15).

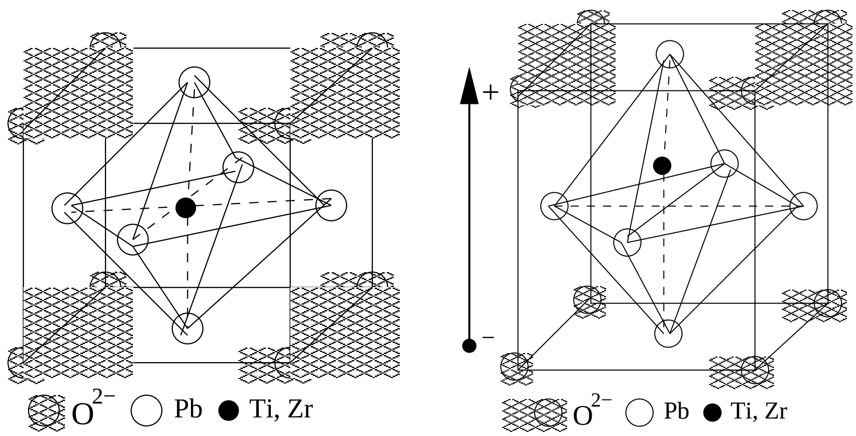

Figure 1: (Left)This is the structure of a molecule of Lead Zirconium Titanate before poling. (Right)This shows the resulting ansiotropic structure of the PZT after poling. (PI 4_15)

Dipoles with parallel orientation are scattered randomly throughout the PZT, prior to its applied voltage, in areas known as Weiss Domains. This electric dipole behavior is caused by the charge separation between the positive and negative ions. When an electric field is presented, the dipoles align, and the structure elongates parallel to the axis of the field. Likewise, the structure contracts perpendicular to the field's axis. This process is depicted in Figure 2 on the following page.

After cooling, the Weiss Domains retain their polarity, as well as the resulting ansiotropic structure, as shown in Figure 1 above.

This process is repeatable. When an already poled PZT receives more voltage,

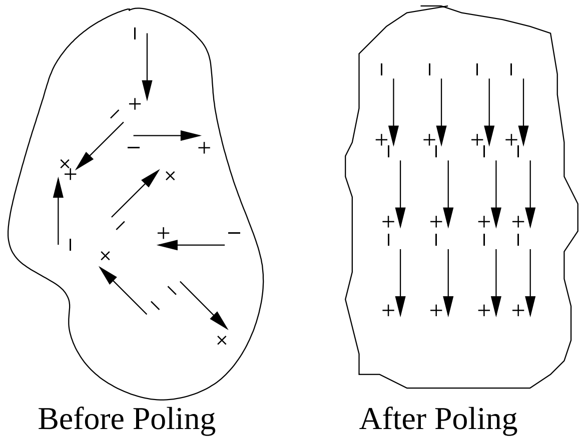

Figure 2: The Wiess Domains of a PZT material before and after poling (PI 4_15).

the Weiss Domains shift in proportion to the new electric field, and the dimensions of the PZT change accordingly.

3 The Michelson Interferometer

Interferometry is an area of study that deals with the properties of interfering light. According to the law of superposition, when two beams of light interfere, the amplitude of the resulting beam is equal to the sum of the individual ampltudes of the two original beams. When two beams interfere, the phase difference – the variations of the resultant amplitudes as calculated by superposition – lead to alternating areas of constuctive and destructive interference, in what are commonly called interference fringes (Ditchburn 114)(Hecht).

In the late 1880's A.A. Michelson set out to measure the length of a light wave. His device used two mirrors and a semi-transparent beamsplitter to cause two beams of light to interfere, creating the interference fringes. The fringes are circular, for reasons that are described in detail in Appendix A.

As used in this project, the Michelson can function as an optical ruler, measuring distances in wavelengths of light. It is the phase differences in the two sources which cause the appearance of fringes. In the Michelson interferometer, because coherent light is used, the phase shift is changed by manipulating the differences in the distances the beams must travel. By changing the distance of one beam, by moving one of the mirrors foward or back, the phase shift is also changed, causing the places of constructive and destructive interference to change, giving the impression that the bullseye fringes are expanding outward, or inward, depending on the movement of the mirror. The exact distance these fringes shift is directly related to the change in the path length.

The basic set-up of a Michelson interferometer is shown in Figure 3.

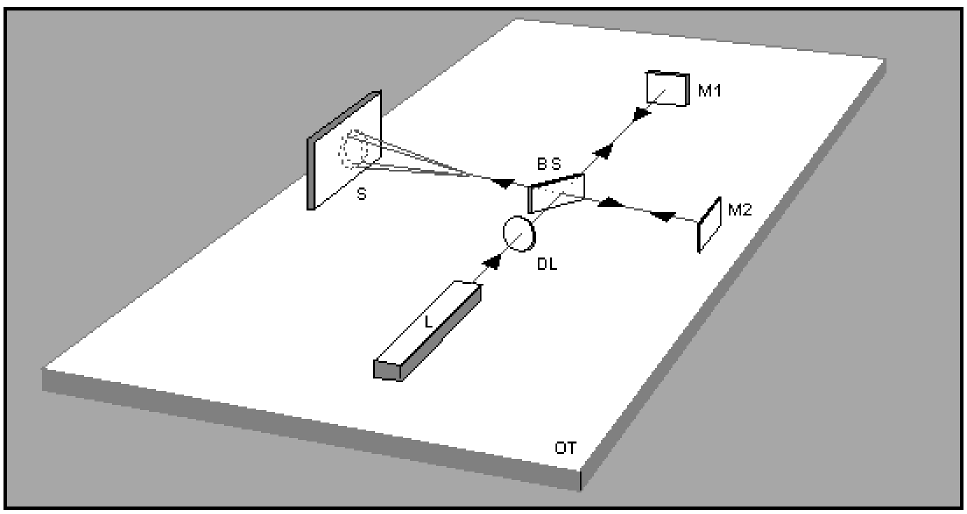

Figure 3: This shows the basic set-up of a Michelson Interferometer. The beam originates from the laser (L), diverges through the lens (DL) and strikes the beam splitter(BS). At this point the original beam splits into two perpendicular beams, one reflecting off mirror M1, the other reflecting off mirror M2. The beams are reflected back to the beam splitter, where they recombine and are projected towards the screen (S). (Image from `http://www.3dimagery.com/parttwo.html`)

4 Experimental Methods and Procedures

Building the whole 'optical ruler' system involved three major steps: arranging the laser, lenses and mirrors to create a laser beam of the correct size, divergence, and position; assembling and aligning the interferometer itself and eliminating unwanted vibrations that initially made the fringes unstable; and finding an efficient method for mounting the PZT behind the moveable interferometer mirror.

Initially the entire apparatus was mounted directly onto a large Newport optics table (5 ft × 8 ft). To achieve better vibration isolation, the interferometer portion was later transferred to a separate 18 in × 18 in × 2 in VERE honeycomb optical breadboard, which was placed onto a sheet of bubblewrap on top of the Newport table. After transferring the interferometer to this breadboard there were still too many vibrations to take any recordings. This was because the relatively heavy 7.5 cm × 5.0 cm × 0.25 cm beam splitter was mounted from the side, and hanging freely. Once the beam splitter was mounted from underneath, the fringes became quite stable.

Standard ThorLabs mounts were used in mounting the laser, both lenses, all four mirrors, beam splitter, and the photodetector. The lenses and photodetector also came from Thorlabs, while the first-surface mirrors came from Edmund Scientific.

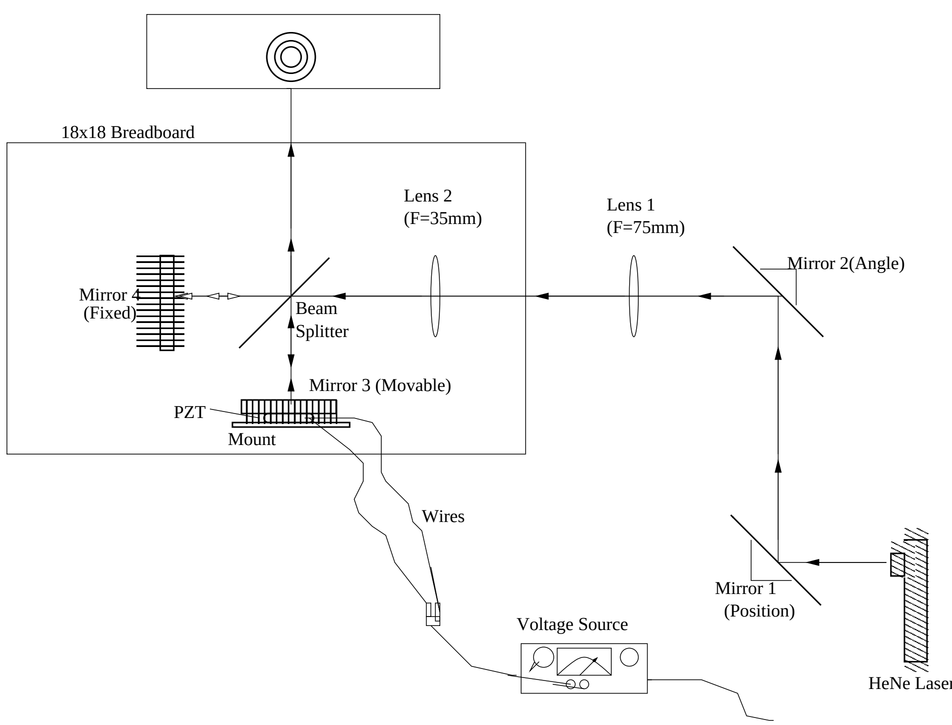

Figure 4: Final arrangement of the complete optical ruler setup.

4.1 Preparing the laser beam

The laser used was a small 1 mW HeNe type originally used in bar-code scanners and now available from surplus companies. The direction of the laser beam tended to drift during the first hour of warmup, but after this was sufficiently stable.

Mirror 1 was mounted 11.5 cm from the laser, angled approximately 45°, to reflect the beam 90 ° to its right. Mirror 2 was mounted 25.0 cm from Mirror 1, also angled 45°, but to reflect the beam 90 ° to its left. These two mirrors were used to easily adjust the angle and position of the beam when directing it into the interferometer. Next, a telescope was assembled using a lens with focal length (FL) 75 mm followed by one with 200 mm FL placed 275 mm further downstream. Since the separation between the two lenses was equal to the sum of their focal lengths, this arrangement expanded and collimated beam.

4.2 Constructing the interferometer

The interferometer was constructed using two first surface mirrors and a beam splitter. The beam splitter was positioned exactly 8.5 cm from the second lens, at a 45° angle. The fixed mirror was mounted 8.5 cm from the beam splitter. For the adjustable mirror, a second first surface mirror was mounted to a standard Thorlabs translating mount, with a micrometer screw, placing it approximately 9 cm from the beam splitter. The finished apparatus is shown in Figure 4.

In order to create the pattern of interference, the mirrors had to be aligned perfectly, and cause the beams to interfere. As mentioned in Appendix A, in order for circular fringes to be obtained, both mirrors in the interferometer had to be exactly perpendicular to the path travelled by the laser beams. During the experimentation, the mirrors were aligned in a specific order, and with a specific method. First, the angle mirror (2) was adjusted using the micrometer screws on the mount until the height and left/right positioning of the beam was constant. Next, the position mirror

(1) was adjusted with the same procedure until the beam was projected to the exact center of both lenses. The lenses had to be exactly the same height, and same distance from right to left. When the beam was only in the center of one lens: first the position mirror would be adjusted to place the beam in the center of the first lens; then the angle mirror was adjusted to place the beam in the center of the second lens. This was repeated until the beam passes through both centers.

Next, before the beam splitter was set in place, mirror 4, the fixed mirror on the interferometer had to be aligned with the micrometer screw until the beam was reflected directly back to the source of the laser. Then the beam splitter could be set in place creating: the transmitted beam which still reflected from mirror 4 back to the laser; and the reflected beam. The beam splitter was angled until the reflected beam was exactly 90 ° from the transmitted beam. At this point, the last mirror was set into place, and adjusted until the reflection of both beams occupied the same space on the screen.

After the beams were so precisely aligned, the interference pattern appeared elliptical. With every trial, and every realignment, circular fringes could not be obtained. By accident however, the second lens in the telescope with FL = 200 mm was replaced with one with FL = 35 mm and instantly circular fringes appeared on the screen. Therefore, it can be postulated that, in order for circular fringes to be obtained, the beam must have a larger diameter, and be diverging. The resultant diameter of the beam at the viewing screen was approximately 10 cm, compared to 1 cm in the original trial.

4.3 Mounting the PZT

The first PZT sample tested was a Physik Instrumente Ceramic 140 (PIC-140) disk with a diameter of 20 mm and a thickness of 1 mm. It was ordered from Polytec PI (Auburn, MA) as part of an assortment of twenty in a PZT Sample Kit. The two circular faces of the disk were coated with a very thin silver film, which acted as electrodes to produce a uniform electric field inside the PZT.

The PZT disk was mounted behind the moveable mirror so that the mirror was supported entirely by the PZT and directly responded to its displacements. This was done using 5-minute epoxy after soldering wires on to the silver contacts.

During the preliminary testing of the apparatus, once the voltage was applied, it took several seconds for even the smallest change to occur in the fringes, and even this movement was very small. After several experiments, it was discovered that these problems were caused by the way the epoxy was originally applied to the PZT, which allowed some epoxy to overlap the sides of the sample. The transducer was actually forcing the epoxy to move along with it, which caused the hesitation in the effect as well as diminishing it.

In the final procedure, much finer wires were used (30 gauge stranded) and these were soldered more quickly on to the PZT, which was set on a block of aluminum as a heat sink. The wires were connected via BNC cables to the voltage supply. Next, a piece of 2 mm sheet metal was epoxied to the face of the mirror mount. A piece of the same material was cut to a size slightly smaller than the PZT, and then epoxied on top of the original piece of sheet metal. The PZT was then epoxied on top of this material, with another small piece of sheet metal glued to the top of it. Finally the first surface mirror was epoxied on top of this. The final PZT mount is illustrated in Figure 5.

Once the PZT was mounted differently, with the epoxy between it and the sheet metal, the applied voltage caused the fringes to shift instantly.

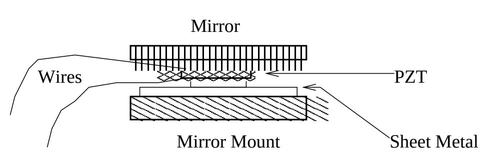

Figure 5: This shows the orientation of the PZT Mount

5 Measurements and Results

A photodetector was used to obtain accurate recordings of the intensity of the center of the fringe pattern. Therefore, low intensities correlate to periods of central destructive interference, and high intensities correlate to periods of central constructive interference.

The photo detector was positioned in the exact center of the fringes, at 0 volts. The voltage was then applied through increments of 10 volts, from 0 – 1000, with the photodetector measuring the resultant intensity of the beam. An intensity vs. voltage graph was then plotted in a spreadsheet program.

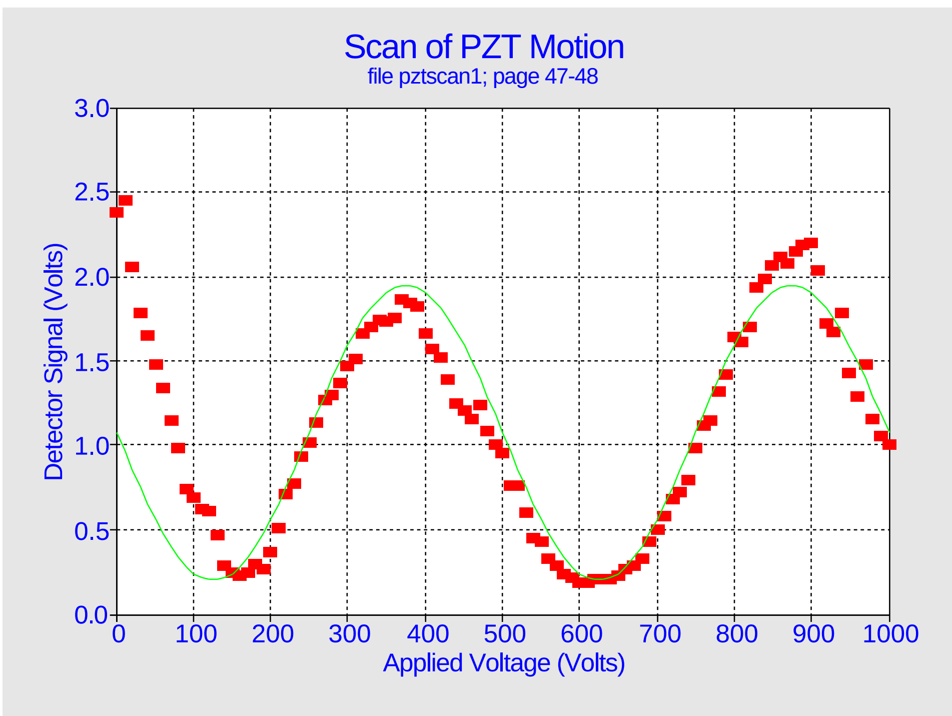

Figure 6: Measured light intensity at the photodector vs. applied voltage (points). The solid line is a sine curve that best matches the data. The period of this sine curve corresponds to the displacement factor.

The results of the intensity vs. applied voltage measurement for the first sample can be seen below in Figure 6. At 0 volts the center fringe was a white spot, or an area of high constructive interference. That is why the first measurements begin at a peak in the curve. As the applied voltage goes up, the changes in the intensity recorded into the photodetector (The points) are closely matched to a sine curve (The solid line) The crests are where the fringes have a white center, and the troughs are times of central destructive interference.

5.1 Calculating the displacement factor

Each wavelength of the sine curve in Figure 6 represented a full wavelength change in the path length, which means the mirror moved a distance of $\frac{\lambda}{2}$. Therefore, the following equation was used to calculate the displacement factor(d) in nanometers per volt, where V_1 equals the voltage at the first crest, V_2 equals the voltage at the second crest and λ equals the wavelength of the laser beam.

$$d = \frac{\lambda}{2(V_2 - V_1)} \tag{1}$$

Inputting 632 nm for λ, 380 V for V_1, and 880 for V_2, the following equation was calculated.

$$d = \frac{632}{2(880 - 380)} \tag{2}$$

Resulting in a displacement factor of:

$$d = \frac{316nm}{500volts} \tag{3}$$

6 Conclusion

Piezoelectric transducers can effectively cause motions on an atomic scale without the slick-slip effect of friction. A Michelson interferometer is an effective tool for measuring this movement. Theoretically, using the displacement factor mentioned above, with .5 volts applied, the PZT will move approximately .3 nanometers. An applied voltage of .005 volts will cause the PZT to displace .003 nanometers. Simply put, this result has implications in nearly every area of science and engineering. With the ability to move objects as small as a blood cell, and the precision to control this movement, to displacements of em exactly 1 nanometer, everything can be made smaller. Gears are now made the size of a hair. Instruments can be made to record even the tiniest pressures. There are devices such as the Atomic Force Microscope which use this principle, and actually work. Almost anything is possible.

In the future, I would like to create a system to automatically record the data. A mount will be constructed to provide for easy exchange of piezoelectric materials to a position behind the movable mirror. Different PZTs of all shapes and sizes, specifically the PIC-155, PIC-150, and PIC-144 from Physik Instrumente can be tested, and the results compared to the original sample.

Then this research can take a multitude of various turns. A feedback loop can be created where a PZT sensor recieves pressure from a vibrating system and transfers it into a readable voltage. This voltage could be used through a series of amplifiers or resistors to create another voltage which would be input into another PZT, translated into a displacement that would counteract and dampen the original vibrations.

Almost anything thought up can be tried and implemented. Only time, and the experiments of the future, can tell what will happen next.

Resources

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Appendix: The Shape of the Interference Fringes

The geometric shape of the fringes can be explained using the following formulas derived from the conceptual image of the Michelson shown in Figure 6.

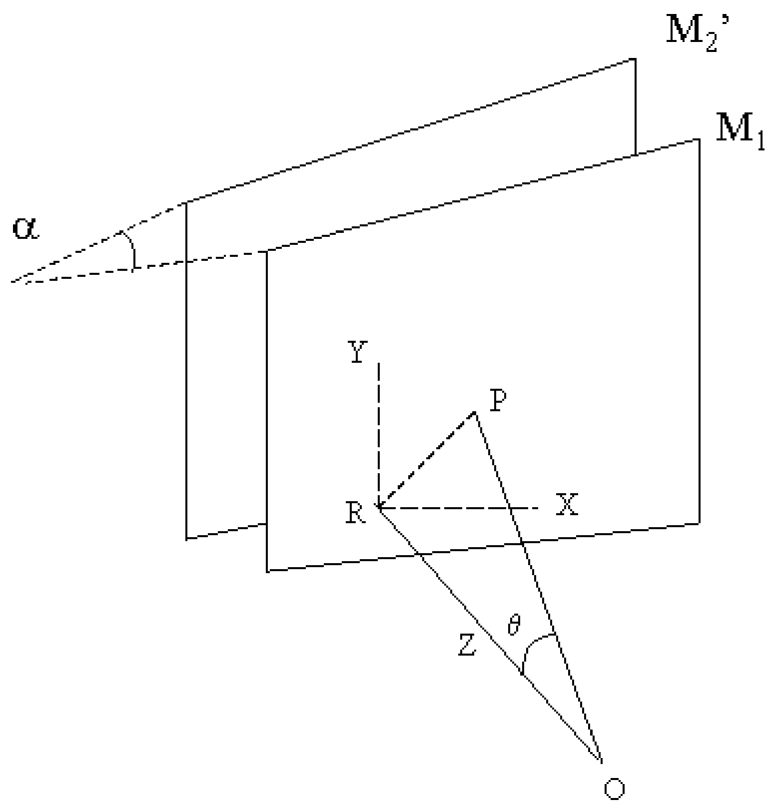

Figure 7: This image represents a theoritical view of the Michelson interferometer, used to get a mathematical view of the resulting interference fringes. (Image obtained from http://www.phy.davidson.edu/sethvc/Fringes/Pages/interference_pictures.htm.)

In the above diagram, M_1 and M_2 represent different planes, or the mirror surfaces of the Michelson interferometer. α is the angle between the planes. 0 is the perpective of the observer, with R at the base of the perpendicular. P is a point on M_1 on the (x, y) and z is the third axis. The first two formulas are derived from basic trigonometry, and geometry.

$$[OP]^2 = (x^2 + y^2 + z^2) \tag{4}$$

$$\cos\Theta = \frac{z}{\sqrt{x^2 + y^2 + z^2}} \tag{5}$$

The distance between the plates at R is equal to e, so the distance at P(d) falls into the following formula.

$$d = e + \tan\alpha \tag{6}$$

Constructive interference always occurs at:

$$n\lambda = 2d/cos\Theta \tag{7}$$

Substituting terms, the equation responsible for the shape of the fringes is as follows.:

$$n\lambda = \frac{2(e + /tan\alpha)z}{\sqrt{x^2 + y^2 + z^2}} \tag{8}$$

If the plates M_1 and M_2 were parallel and angle $\tan\alpha$ was equal to 0, the following equation would result,

$$n\lambda = \frac{2ez}{\sqrt{x^2 + y^2 + z^2}} \tag{9}$$

which is equal to

$$x^2 + y^2 = \frac{4e^2}{n^2\lambda^2} - 1z^2 \tag{10}$$

the equation of a circle. Therefore, when the mirrors of the Michelson interferometer are exactly perpendicular, or the conceptual plates where the beams reflect are exactly parallel, the resulting fringes appear circular (Davidson)(Tolansky).