Optical Position Sensors with Applications in Servo Feedback Subwoofer Control

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Abstract

Loudspeaker distortion may be reduced by means of servo feedback control using measurements of the speaker movement. There are advantages to using position sensing over velocity or acceleration sensing, but direct position sensing is also much more difficult to incorporate into a loudspeaker. This project surveyed various optical position sensing schemes for a subwoofer loudspeaker, and discusses a design for a commercially viable and inexpensive optical position sensor. Testing found this sensor design to be highly accurate for tracking voice coil position, but cone breakup non-linearities prevented successful distortion reduction via feedback. Future work discusses solutions to this engineering problem.

Introduction

Design Goals: a woofer for electrostatic speakers

Well-designed, full-range electrostatic speakers can reproduce music with excellent transparency and lack of coloration, but due to the physics of their design they are limited to moderate volumes and cannot extend to the lower bass frequencies. A subwoofer is often needed to fill out the bass, but dynamic woofers generally fail to properly blend with the electrostatic speakers because woofer designs typically sacrifice precise bass reproduction to achieve higher maximum sound pressure levels (SPLs).

The purpose of this project is to create a feedback sensor design for use in a woofer that is optimized for integration with electrostatic speakers. Since the woofer does not have to play at excessively loud volumes, it will use just an 8" diameter driver, thus the sensor will have constraints that limit its size. Distortion is minimized through careful speaker design and the use of position sensing servo feedback.

Woofer Servo Feedback Overview

The purpose of the servo feedback is to minimize the woofer's harmonic distortion. This is not an original idea unto itself, many subwoofers are currently available that use feedback to reduce distortion [1, 2, 3]. There exist a variety of methods of acquiring a feedback signal from a subwoofer speaker [4], a few of which are examined here.

The current industry standard for feedback woofer designs use accelerometers to measure the speaker's acceleration, and from the acceleration data calculate a woofer's position. Problems with this method come from inherent bandwidth limitations of the sensors: accelerometers are unable to detect a slow drift over time away from the speaker's center position. This drift will inevitably cause the speaker to clip at lower amplitudes, introducing large amounts of distortion. To avoid this, one can assume that current feedback woofer designs use very small amounts of feedback in their control loops. Unfortunately, at these low levels the benefits from the feedback control are also minimal, if any. Another issue with accelerometers is that they must be coupled with the speaker cone; therefore they add mass to the system which will raise the speakers quality factor (Q), which results in peaky response; and also lower the resonant frequency.

Some speaker designs also use a dual voice coil to make velocity measurements. This method adds a second voice coil which acts in reverse to the drive coil. The movement of the cone induces a current in the sensing coil, which can then be sent back to a feedback circuit. This method also has bandwidth limitations, as well as imparting a force upon the speaker in order use electromagnetism to generate a current.

Alternatively, direct position measurement for tracking the motion of a woofer does not have the drift problem, and thus prevents the speaker from reaching conditions that would induce premature clipping. With position measurement, there is an absolute center speaker position that will not change over time.

While there are numerous cheap and easy ways to measure woofer cone acceleration, direct position measurement is more difficult. The reason industry uses acceleration rather than position sensing is because there is an abundance of small and inexpensive accelerometers that are easy to mechanically integrate into a speaker design. Therefore, the primary goal for this project was to design a simple and inexpensive method for measuring the woofer's position.

Design Requirements

Since this design is meant for eventual production by Music Reference of Santa Barbara, CA, there were certain engineering requirements that needed to be met to achieve the design goals of the woofer. First and foremost, the position sensing needed to be able to accurately track the motion of the speaker through its entire range of motion. The dynamic driver used for prototyping was an Eminence model 8-1500, which has a maximum excursion specification of 6.8mm (approximately ¼ inch). Therefore, the sensor must be able to track the motion through the entire ½ inch range of the speaker.

The client also specified that the sensor must be linear to within 1%. This was to be verified using linear regression on the sensor measured position versus actual cone position, and finding the coefficient of determination (R^2) for the usable region of that sensing scheme. As long as $R^2 \geq 0.99$, then the linearity criterion was met.

The client also desired the sensor to have an analog voltage output in order to easily integrate it into an analog feedback loop. While digital feedback can offer excellent control based on predictive models of the speaker dynamics in addition to the measured input, the client did not want the additional cost and complexity of digital control hardware. In this case, with a quality position sensor, inexpensive analog control would meet the client's engineering criteria.

Finally, the client required that the position sensor must be inexpensive, with a general guideline that specialty materials cost should be less than $30 per unit (in quantities of 100 units) to add feedback to the woofer. This cost does not include the price for conventional electronic components such as resistors, capacitors, op-amps, regulators, and so forth.

Optical Speaker Position Sensing Approaches

Before going in to the details of various approaches for tracking the position of a speaker cone as it moves, it is worthwhile to have a quick refresher on the components of a speaker. The part of a speaker that is normally visible is called the speaker cone, and this is what creates the sound. The speaker cone is attached to the voice coil, which has wires wound all around it through which runs the electrical current that the speaker receives from the amplifier. Surrounding the voice coil on the inside and outside is a magnet, with the portion of the magnet inside the voice coil called the pole piece. When alternating current runs through the voice coil, an electromagnetic force between the moveable voice coil and stationary magnet causes the voice coil to move up and down, in turn causing the speaker cone to move up and down. This motion pushes the air in front of the speaker cone, and creates the sound waves that we all hear.

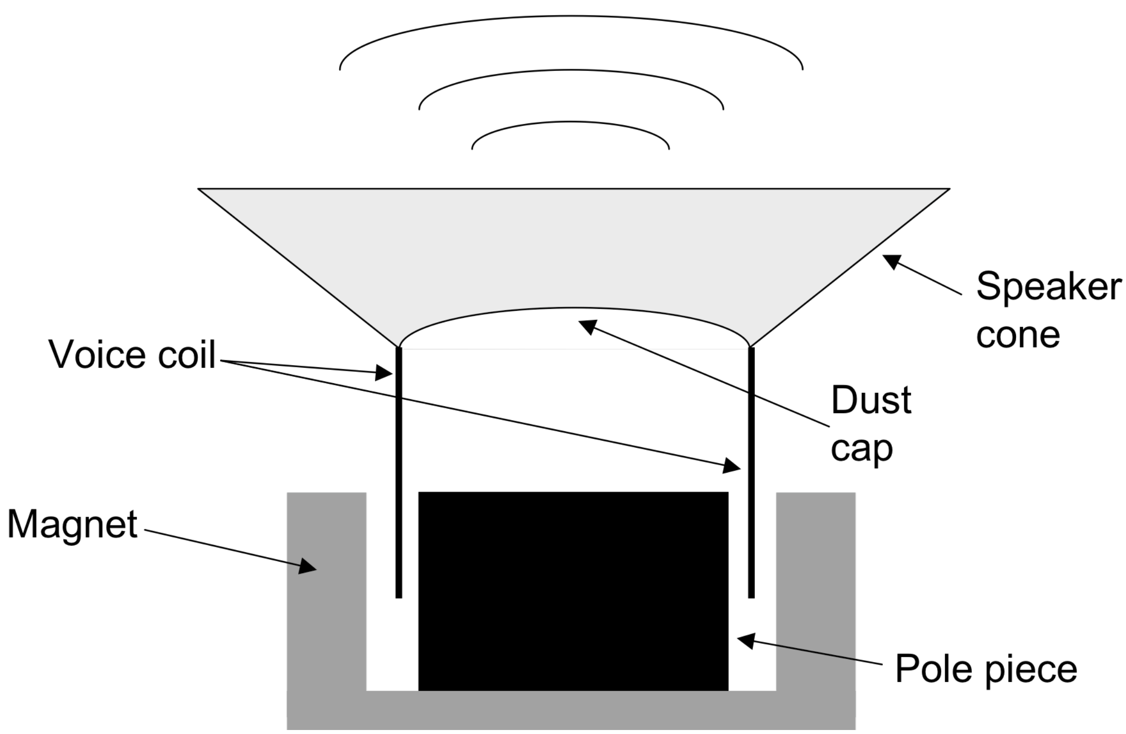

Figure 1 - The components of a speaker (not to scale)

Point Source, Point Receiver

One common method of non-obtrusive position sensing is through the use of infrared emitters and receivers. Such a scheme can be implemented with discrete sensors, or integrated emitter/receiver packages such as the popular GP2 series made by Sharp. The principle behind this is that the infrared light disperses as you gain distance from an IR emitter. Therefore, a sensor will pick up less light from the emitter if the emitter is moved farther away.

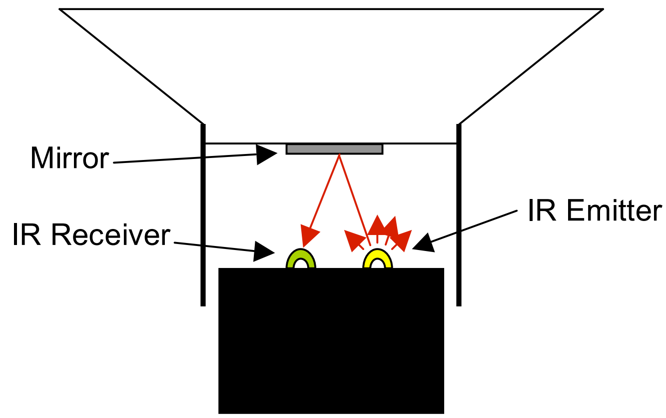

Figure 2 - Point Light Source, Point Receiver

In a loudspeaker, this principle could be put to work by coupling a mirror to the voice coil. As the speaker moves, the distance the light must travel will change, and more or less light will hit the receiver. One could also attach one of the components to the voice coil, thus eliminating the need for a mirror. The approach would have technical issues to resolve by having a powered device attached to a moving voice coil.

Point Source, Linear Receiver

Another way of measuring the driver position is to attach a narrow beam light source to the pole piece, aim the light beam at a mirror coupled to the voice coil, and have the reflected beam hit a position sensitive detector (PSD) photodiode [10]. A PSD works by varying the output current based on the position of a spot of light that hits the sensor surface.

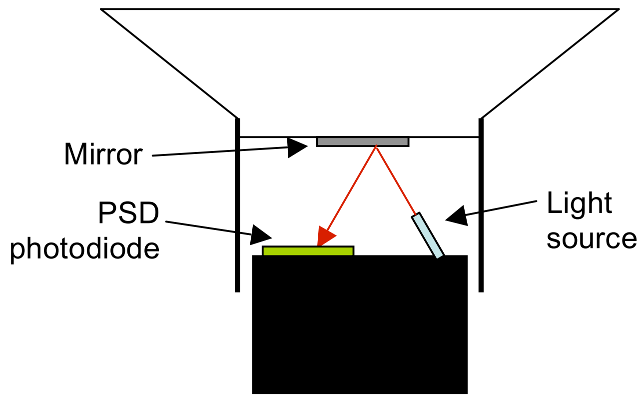

Figure 3 – PSD and narrow beam light source position detection

Figure 3 shows how the position of the light beam hitting the PSD correlates to the position of the speaker using simple geometry with an angled light beam and reflector. The light beam can originate from a focused LED or a laser diode.

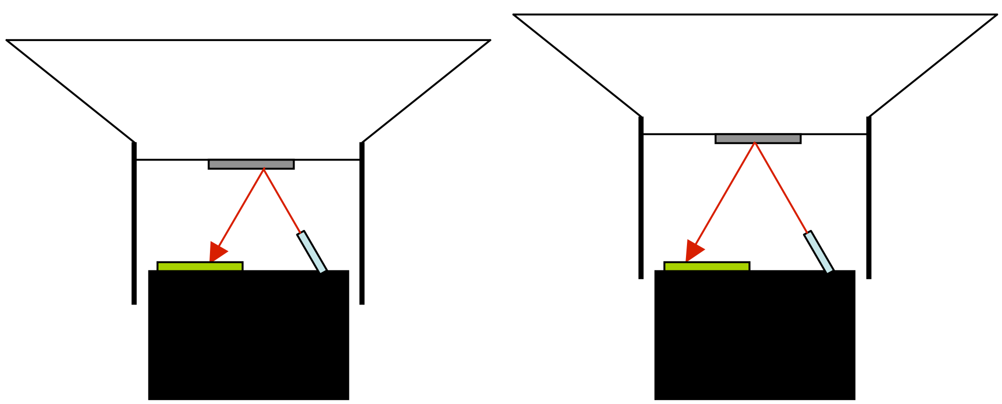

Figure 4 – PSD output varies with laser position

Alternative methods of configuring a PSD sensor include mounting the PSD vertically rather than horizontally. This would ensure the path the light source took to reach the PSD would be equidistant regardless of the speaker position, resulting in a more consistent spot size over the entire travel of the speaker. One could also mount the light source or PSD directly onto the voice coil, thus omitting the need for a mirror. Technical issues arise though when coupling a powered device to a moving voice coil.

Linear Light Source, Linear Receiver

This method of driver position measurement uses a linear light source and a thin rectangular photodiode attached to the pole piece, and an opaque vane supported by a crossbar attached to the voice coil. The voice coil and speaker move in and out, while the pole piece always remains in a fixed position.

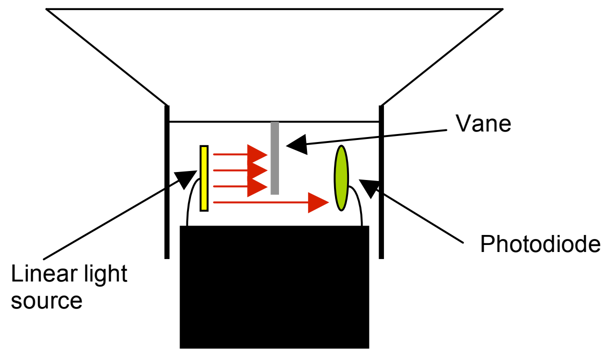

Figure 5 – Linear light source position measurement

The woofer's movement varies the amount of light that the vane shades from the photodiode. With a linear light source such as a linear incandescent lamp, cold cathode fluorescent tube, linear LED, or electroluminescent wire, the amount of light reaching the photodiode directly correlates to the position of the woofer.

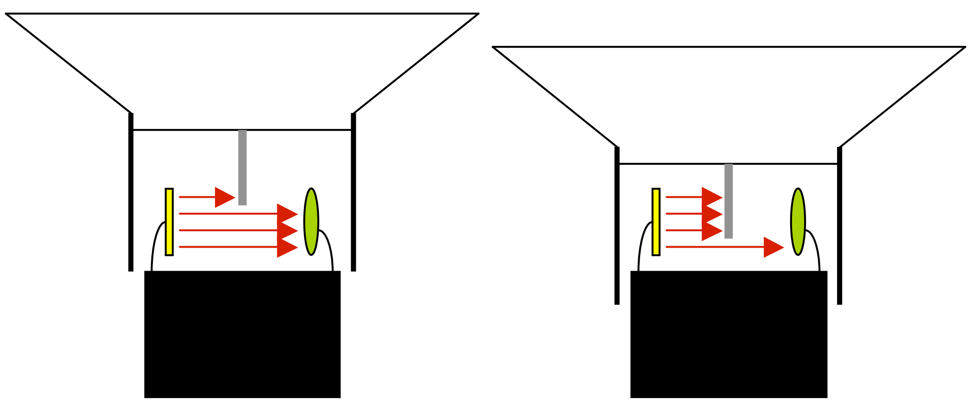

Figure 6 – Light sensed changes with speaker position

Music Reference once tried this method 20 years ago using a linear incandescent lamp, but had problems with the woofer's movement causing the filament to vibrate. The vibration introduced distortion into the feedback signal, which was unacceptable. Over the years, technological advances have made it such that a solid state light source could now be used. A solid state light source such as an LED would not be susceptible to any change in output under any conditions it would experience inside the woofer's voice coil.

Linear Optical Encoders

Linear optical encoders are sensing devices consisting of a readhead and a scale. The scale contains numerous miniature stripes that can be read by the readhead. As it passes over the scale, the readhead counts the number of stripes that it sees, and can use that then to determine the position. In the case of a speaker, the scale would mount onto the voice coil, while the readhead would rest on the pole piece.

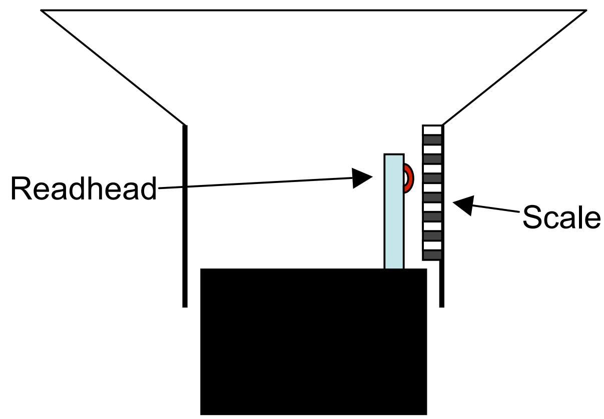

Figure 7 – Speaker position sensing with a linear optical encoder

Since optical encoders are inherently a digital sensing method, one must ensure that the rate of the stripes passing by would not exceed the sampling rate of the readhead, causing aliasing in the signal.

This sensing method was never prototyped due to the high cost of linear optical encoders, and the requirement of a microprocessor and D/A chips to convert the signal to an analog output. While this technology would theoretically perform quite well, the high cost and complexity of this scheme prevented it from further consideration.

Speaker Position Sensors

The following is a more thorough look at the various sensing methods that were examined in choosing the final design for the woofer sensor. This includes a description of the methodology, equipment needed, cost estimate, and pros and cons for each sensing method. All cost estimates are in cost / unit in quantities of 100 units ordered from Digikey or Mouser.

Infrared Point Sensors – Packaged and Discrete

One of the most common methods of measuring short distances in robotics is with the use of solid state infrared (IR) sensors. This includes the use of an infrared LED as the emitter and a phototransistor or photodiode as the receiver. Emitters/receiver pairs can be assembled from discrete components, or they may come in integrated packages with convenient interfaces. One of the most common of these is the Sharp GP2 series [5, 6], which are available in a large variety of distance measuring ranges. The GP2D120 [7] has an effective measuring range between 4 and 60cm.

Figure 8 - Sharp GP2D120 Analog IR Position Sensor

While the convenience of an all-in-one package and plugable interface make this an attractive position sensor, there were two major drawbacks. First, the output of the sensor was not linearly dependent on the distance to the reflective object (see Figure 9). One could find the correct mathematical function to apply to the output voltage in order to compensate for the non-linearity, or linearize the output through brute force with a lookup table, but these approaches would both require a digital controller that would exceed the budget constraints of this design.

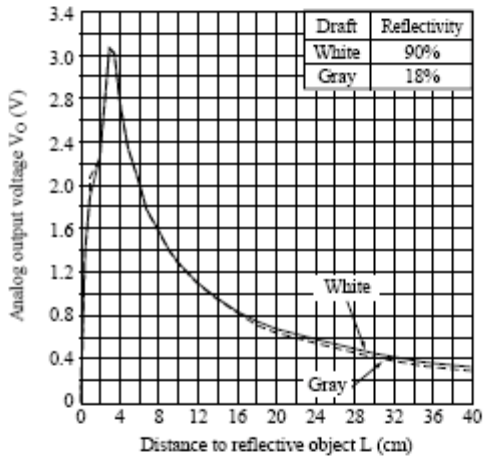

Figure 9 - Sharp GP2D120 output voltage vs. distance to object

The other drawback to this sensor is that the output is not a pure analog output. While the output is analog in value (not quantized), the Sharp sensor does not make continuous measurements in the time domain. Instead, it uses light pulses in regular intervals along with an internal signal processing circuit in order to filter out the effects of ambient light changes from the measurements. This is a necessary feature in order to enable the sensor to detect positions independent of the amount of ambient light.

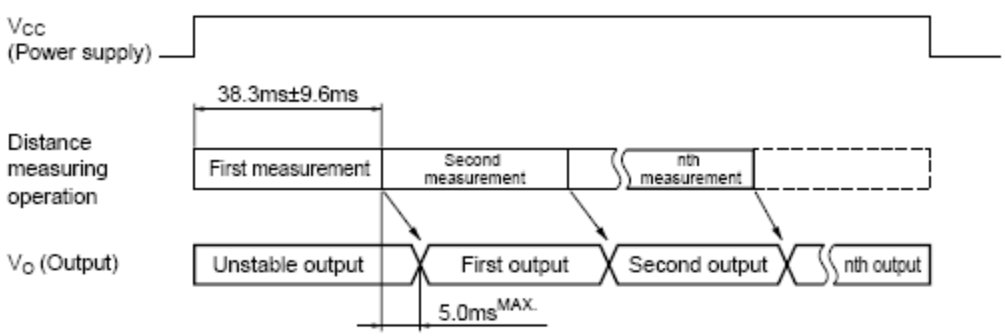

Figure 10 - Sharp GP2D120 Timing Chart

The timing chart in Figure 10 though shows that the Sharp sensor has a sampling rate of 38.3 ms, which equates to 26 Hz. The woofer's low-pass cutoff could occur as high as 100 Hz, therefore the 26 Hz sampling rate is much too slow for this application.

The signal processing used to filter out ambient light is unnecessary for a subwoofer design, since the sensors would be enclosed inside the subwoofer in complete darkness. To test then if infrared position sensing could be used without having to split the output into discrete samples, we looked to discrete infrared emitters and receivers. For prototyping, we chose to test with the Lite-On LTE-302 emitter [8] and Lite-On LTR-301 receiver [9]. These were attractive options due to their exceedingly low cost (both less than $0.20 each).

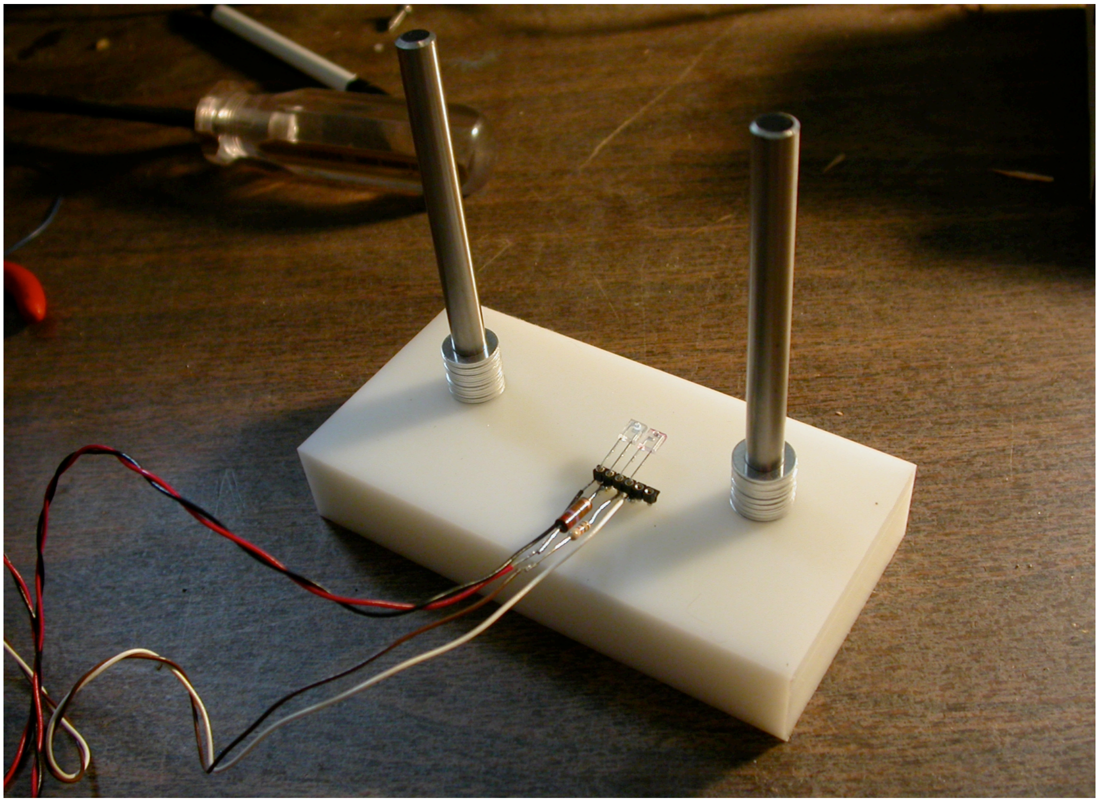

Figure 11 - IR emitter and receiver mounted to the measuring device

In order to prototype the linearity of the sensors using the reflector approach described in Figure 2, we machined a test apparatus that used precision washers and a mirror polished cross beam to adjust the distance from the sensors to the mirror surface. By adding or removing washers, one could precisely adjust the height of the mirrored cross-beam.

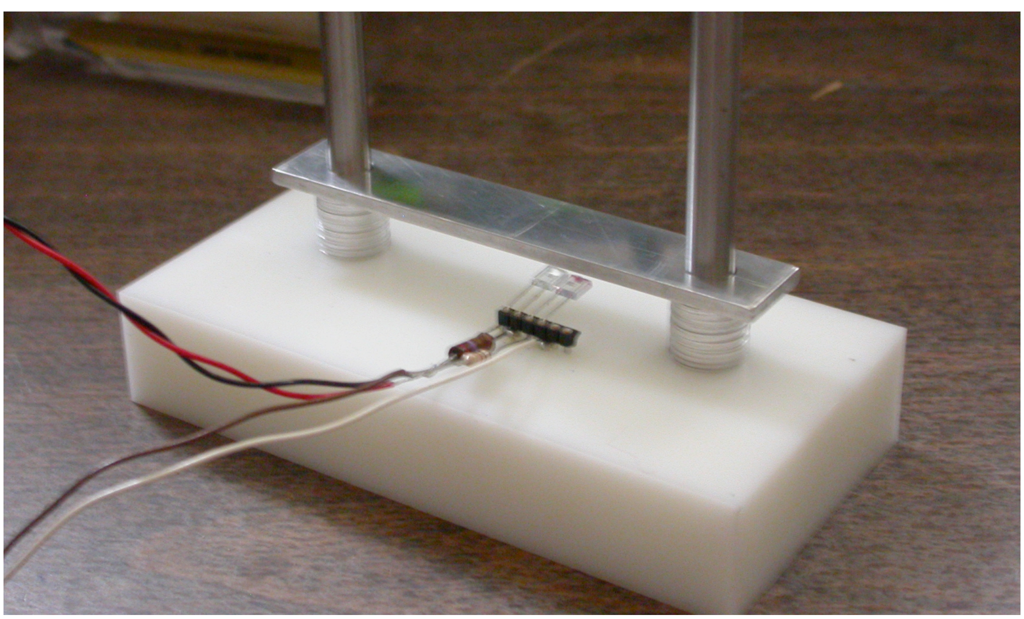

Figure 12 - The mirror height is adjusted by adding or removing washers

While using discrete IR sensors resolves the sampling issue found in the Sharp sensors, the output still suffered from non-linearities. Figure 13 shows the same inverse relationship of the measured sensor voltage to mirror distance as seen in the Sharp sensor. A linear regression on the measurements in Figure 13 result in an $R^2 = 0.91$, meaning that there is a 9% non-linearity to the output.

Figure 13 - Discrete IR sensor output voltage vs. distance

In general, this asymptotical nature will be found in any point source, point receiver sensing scheme. This is due to the physics of field dispersion of a point source, where there is an inverse squared relationship between distance and field strength. Sound wave and visible light dispersions also operate on the same principle, and can be observed with experiments using a dB meter or light meter respectively. Since this is the case for all point source sensors, other sensing tactics had to be used in order to achieve a linear output.

Position Sensing Detectors (PSDs) with LEDs and Laser Diodes

A position sensing detector (PSD) is a monolithic (single chip) PIN photodiode with a uniform resistance in one or two dimensions. When a spot of light hits the PSD, it acts as a potentiometer for two current paths created by a reverse voltage bias going into the common electrode. Depending on where the light hits, it varies the distance that electrical current must travel across the resistive layer from its DC biased common cathode to the sensor's two outputs (X1 and X2). The output current for each electrode is directly proportional to the resistance (and in turn distance) of the path to the output. The position conversion formula [10] for this sensor is as follows:

$$\frac{I_{X2} - I_{X1}}{I_{X2} + I_{X1}} = \frac{2X_A}{L_X}$$ (See figure 13 for definition of terms).

The benefit of the above conversion formula is that since you are comparing the ratio of the current difference to the total current, it is independent of any fluctuations in overall ambient light, light spot brightness and size, and bias voltage. A current mirror and current to voltage op-amp circuit measures the total input current, and another op-amp circuit can measure the current difference of the two outputs. The problem comes when it's time to divide the values. With analog circuitry, this requires using a logarithm ratio integrated circuit such as the AD538. Hamamatsu sells a readymade circuit card to interface with a 1-dimensional PSD and perform the necessary calculations, but this card costs many hundreds of dollars and was outside the budget of this project.

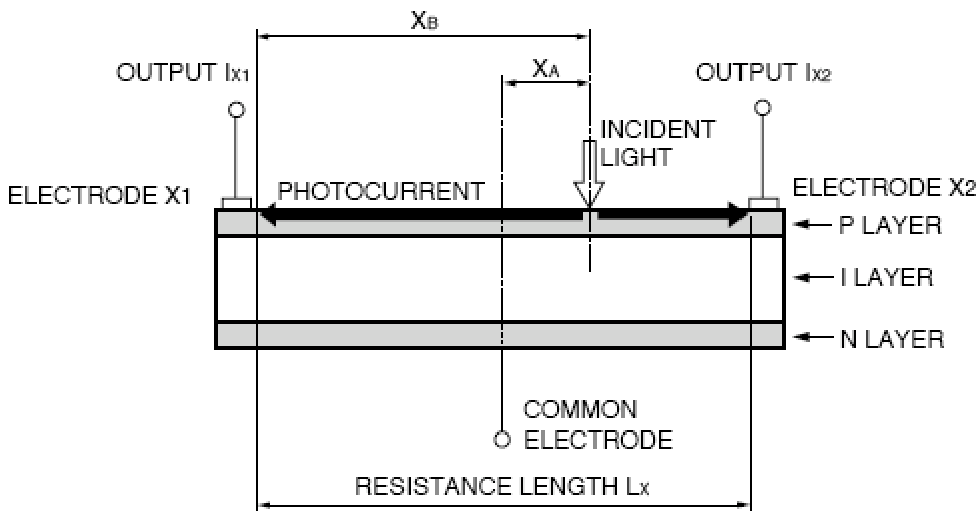

Figure 14 - One dimensional PSD sectional view

Making a few assumptions with the conditions that the PSD would encounter inside the subwoofer, it's possible to simplify the position conversion formula to not require any expensive math IC chips. Since the sensor would be in complete darkness, ambient light conditions would not change. Also, a quality power supply would ensure that the input voltage bias and the intensity of the incident light would remain constant. The geometry conveyed in Figure 3 would vary the spot size as the woofer moved, therefore varying the spot intensity. Figure 15 diagrams two alternative configurations that would deliver a constant light path distance, ensuring a constant spot size on the sensor.

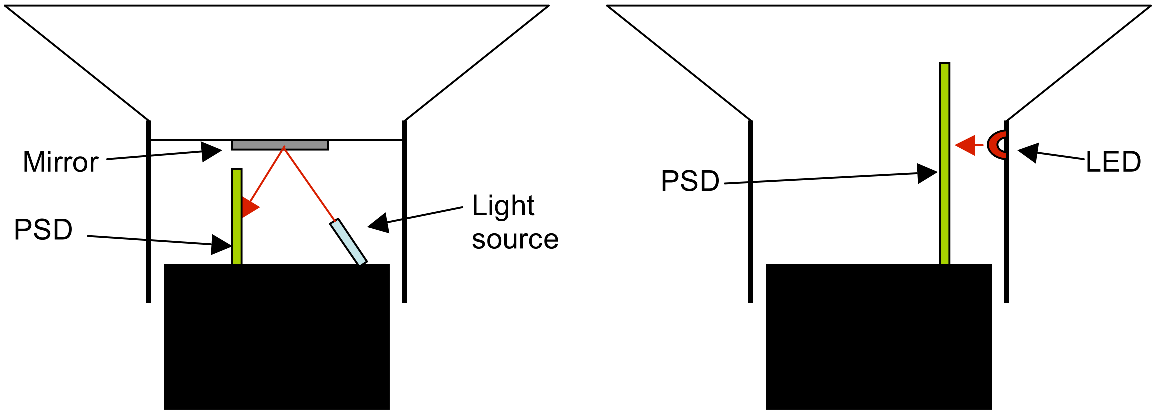

Figure 15 - PSD configurations with constant light path distances

Once these conditions are met, only one of the outputs of the PSD needs to be measured. The position conversion formula is vastly simplified to the point where current from the non-grounded output is proportional to the distance of the light spot from the grounded electrode, where X_B is the distance from the grounded electrode to the incident light.

$$I_{X2} = \alpha \frac{X_B}{L_X}$$

The proportionality constant α is dependent on the value of the gain resistor in a current to voltage converter op-amp circuit connected to the output of the PSD.

Prototyping for this project was performed using a Hamamatsu S3932 [11, 12], although if the design were to go to production it would likely use a model S8543 instead because it is half the cost and has a longer active area. The shorter S3932 was used for prototyping though because it was a through-hole design rather than surface mount, making it easier to mount the sensor and attach wires to the leads. Otherwise, both sensors behave equally.

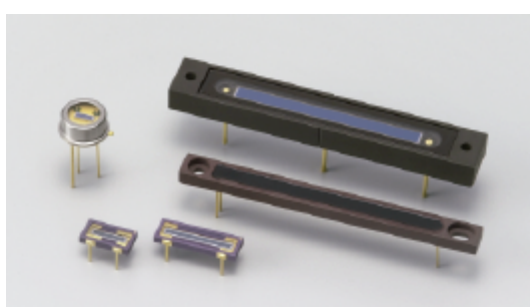

Figure 16 - A selection of 1-dimensional PSDs

For a light source, initial prototyping was performed with a Hamamatsu L7868-02 lensed LED. The lens on this particular LED causes the light emitted to be more focused than a typical LED. For the L7868, the relative radiant output reaches 50% of the peak at 2.5° from the center axis. This results in a highly focused beam of light, projecting a small spot onto the PSD.

To test the linearity of the PSD/LED system, the LED was mounted onto a blade micrometer in order to make precise position measurements while moving it along the length of the PSD. A regulated power supply was used for the bias voltage and LED current, and ambient light levels were controlled so that it was only necessary to measure the output current from one terminal of the PSD (X1). The other output terminal (X2) was grounded.

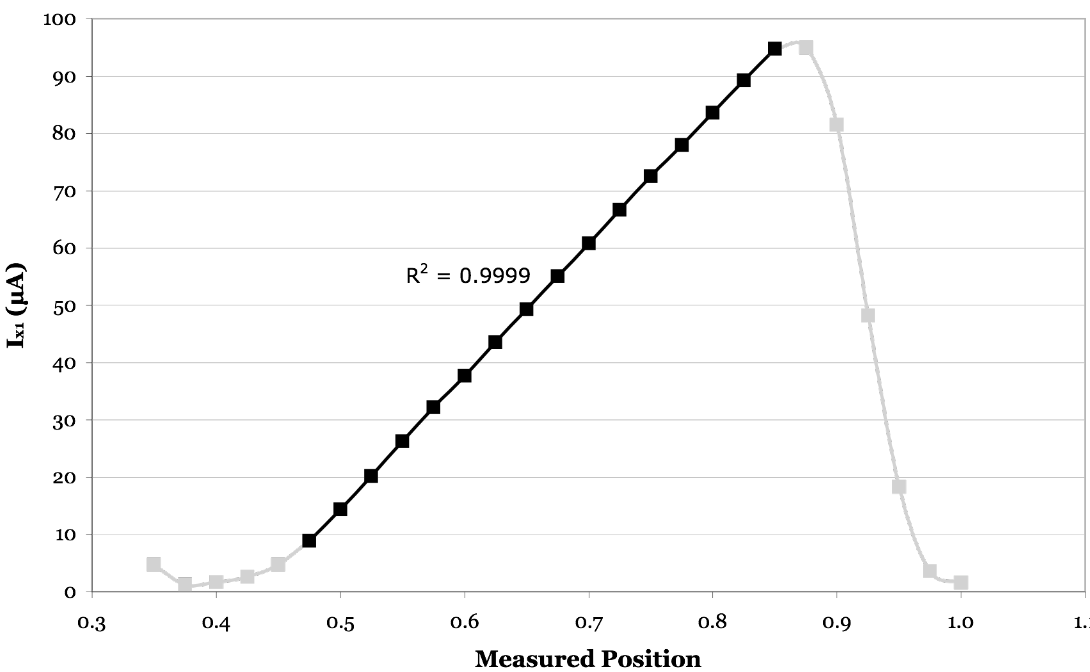

Figure 17 - PSD linearity with focused LED light source.

Figure 17 shows the results from this experiment, with the x-axis representing the spotlight position as measured by the blade micrometer, and the y-axis representing the output current from the PSD. In the chart, the spotlight position should be classified as interval data, since the starting point was arbitrary. The tests showed an excellent linear region where the output current was proportional to the position of the LED spot. On either side of the linear region were the regions where the signal ramped due to only a portion of the LED spot being on the sensor. The sensor used in the testing had an active length of 0.5 inches, but the linear region only had a length of 0.4 inches. Despite the LED being highly focused, it still had enough of a width that caused the linear region to shorten.

In order to reduce the shortening of the viable sensor region, we tried using a more tightly focused light source. Laser diodes are cheap, small, and inexpensive, and present another option as a light emitter. With a 0.045° dispersion angle, laser diodes achieve a much closer approximation to an ideal point light source. Their added weight from the brass casing holding the lens though means that they would not be able to be mounted on the speaker voice coil. If implemented, this would present additional design challenges on how to mount everything onto the speaker.

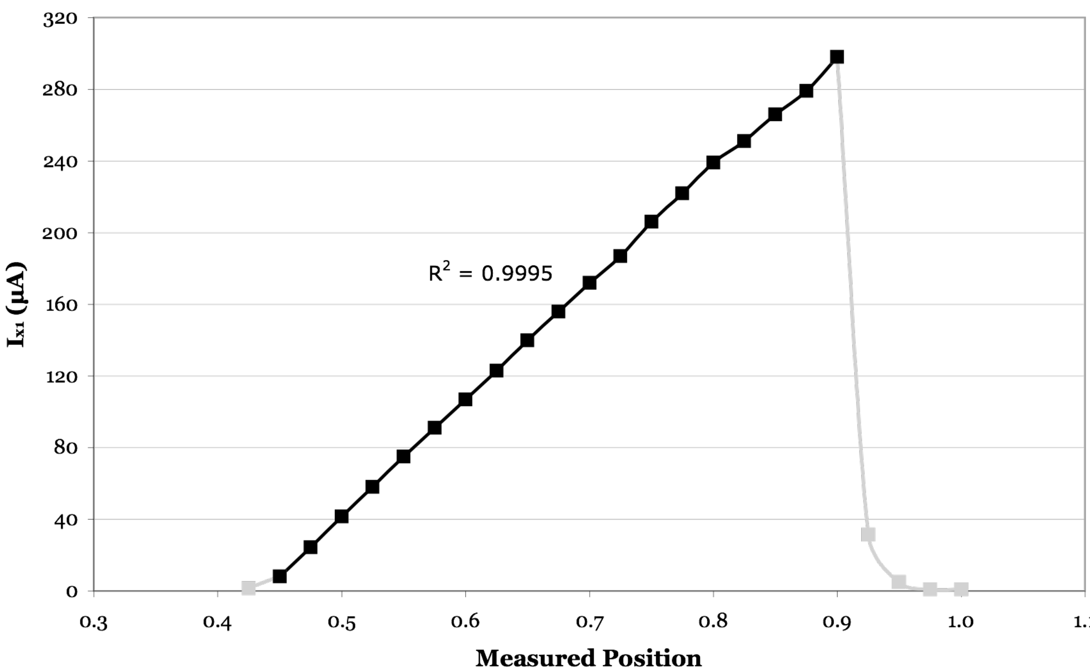

Figure 18 - PSD linearity with laser diode light source

Figure 18 shows the results of linearity tests on the S3932 PSD using a generic 5mW 650nm laser diode. With the smaller spot size, the linear region was extended to 0.45 inches, with much sharper cutoffs at the ends. The higher intensity light resulted in three times as much output current from the PSD sensor. The only drawback with the smaller spot size was that it made the system more sensitive to slight perturbations. Because of this, the linear region wasn't quite as smooth as that measured with a larger spot from the focused LED, and great care would be needed to mount components in such a way to make them absolutely fixed with no possibility of any perturbations.

While the PSD linearity measurements were excellent, manufacturability concerns regarding PSD fitment and the need to mount electrical components to the voice coil, in addition to the high price of the PSDs, were responsible for ruling out this sensing scheme from the final design.

It is worth noting that Wolfgang Geiger published a paper in the *Journal of the Audio Engineering Society* on using a PSD to implement position servo feedback control on a loudspeaker [13]. While my tests have confirmed his find that PSDs can in fact be used for speaker position sensing, his implementation was not a robust design capable of mass production. The way that he mounted the PSD sensor to the pole piece required the speaker to not have a dust cap. This is okay for a proof of concept in a sterile lab environment to test the effectiveness of position sensing servo feedback, but a production design though would require a dust cap to prevent particles from entering and getting lodged in the voice coil, which would eventually destroy the driver. Also, there are long term reliability problems with mounting electrical components to the voice coil. The vibration of the speaker would undoubtedly cause the solder joints to eventually fail [14].

Linear Sensors – Fiber Optics (Send and Receive)

To test the viability of the linear light source, linear receiver scheme, it was necessary to find sensors and receivers that fit that particular geometry. One preliminary design that was prototyped used fiber optic cables. The theory was to couple an light source or light receiver to one end of the bundled fiber optic cable, then on the other end to spread out the fibers uniformly and clamp them together to create the line sensor.

To determine the viability of this method, a proof of concept was created by machining an aluminum bracket that could hold two opposing splayed fiber optic cables. Each side contained a shallow recess slightly less than the thickness of a single fiber optic strand. On either side of each recess were threaded holes to take screws that held down flat top plates to clamp down on the fiber optic strands. On the other side of the cables, coupling a light source or receiver to the bundled cable was accomplished with heat-activated shrink tubing.

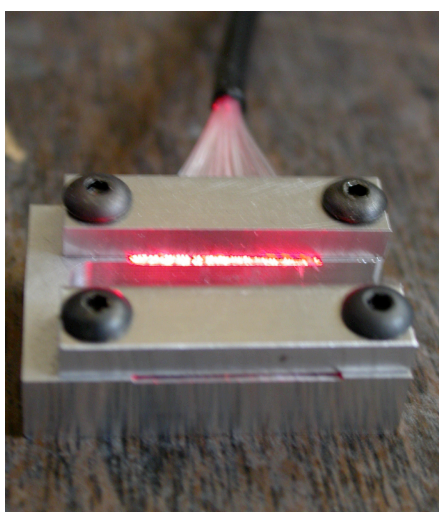

Figure 19 - LED fiber optic light source

In practice, creating this kind of light source proved to be a difficult task. On the linear side, it was time consuming and required a lot of patience to splay out the fiber optic strands into a uniform fan. And while tightening the clamping screws, it was easy for the cable to slide out or the strands to slip into non-uniformity. The bundled side was no easier to manufacture. Since most LEDs have rounded casings and emit a non-uniform light distribution, there was high variation of light uniformity on the fiber optic line with just the slightest movement of the LED. The rounded nature of the LED casing made it very easy for the LED to move from the desired position as the heat tubing enshrouded the parts. We attempted to reduce the slipping by flattening out an LED casing for better mechanical fit pressed against the bundled cable, but this also adversely affected the light distribution, decreasing the uniformity of the light emanating from the output. Figure 19 shows the best attempt at a light emitter that we could achieve using an LED light source, where it is clear that there is still not a consistent light brightness across the line.

Figure 20 shows another attempt at a line source using an incandescent light with a makeshift tin foil reflector coupled to the fiber optic cable rather than an LED. This resulted in a much improved uniformity, but even so did not result in a perfect line source (in the photo, one can see that the right third of the light line is slightly brighter than the rest).

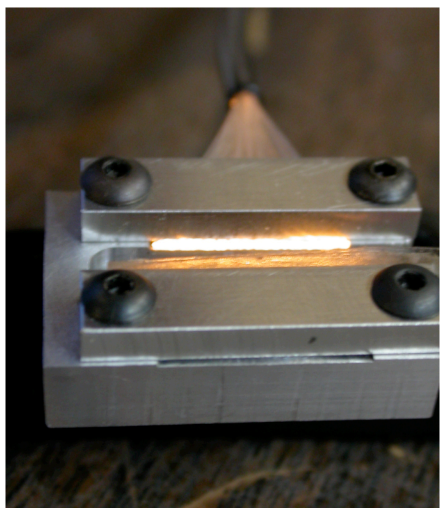

Figure 20 - Incandescent fiber optic light source

All of these manufacturing difficulties were encountered for making the light source side despite the guidance during construction of being able to see the light emitted to ensure the uniformity of the sensor. A receiver would have no such feedback, and would be virtually impossible to create as a consistent line receiver. Since the fiber optic scheme was fundamentally non-linear, and took much effort to even approximate linearity, this method of sensor was deemed unsuitable to this application.

Linear Receivers – Photodiodes

After experimenting with the fiber optics, it became clear that an inherently linear sensor would be necessary for the line-source/line-receiver scheme to work properly. A photodiode is a transducer that converts light to electrical current. Used in photovoltaic panels, photodiodes may sometimes be called solar cells. Photodiodes come in many shapes and sizes, and for this application we desired a cell that was at least as long as the maximum travel of the speaker (>0.5 inches), yet narrow enough to fit inside the vent hole of the prototype speaker's pole piece.

Figure 21 - Advanced Photonix Silicon PIN Photodiode (PDB-V612-2)

One company, Advanced Photonix, makes a photodiode that meets these criteria (shown in Figure 20). These can be bought for $11.61 each in quantities of 100, so they fit within the low cost goals of the project.

Photodiodes are linear in output current with respect to input light, but the output current cannot be measured by putting a resistor in series with the cell and measuring the resultant voltage because photocells have a very low compliance (maximum voltage output). The compliance of the PDB-V612 is approximately 0.4 volts. The proper way to acquire a voltage signal from a photocell is to place it in a current to voltage converting op-amp circuit [15]. This keeps the cell from ever exceeding its compliance limit, and provides a stable and reliable voltage conversion that can also be easily low-pass filtered for noise reduction if necessary.

These chips have a saturation current of 800 µA, meaning that if you shine a bright light on the cell, it will output that much current. One nice property is that this saturation is area dependent, such that if you cover half the cell, then the saturation current will become 400 µA. When selecting a light source to pair with the photodiode in the light vane configuration, if one chooses a source that is much brighter than what is necessary to reach the cell's saturation point, then this allows the light source intensity to fluctuate and not affect the output of the sensor. Therefore, one can take advantage of the area saturation property of the photodiode to eliminate signal noise due to the light source by ensuring that the light source is bright enough for the sensor to exceed its saturation point.

Linear Sources – LED Arrays

As mentioned earlier, Music Reference had previously tried to make a linear position sensor using photodiodes and an incandescent line light source, but encountered problems with the magnetic fields in the speaker cone causing the light filament to vibrate and add noise to the signal. To eliminate this problem, we first tried to find a solid state linear light source instead.

Lumex specializes in making cheap solid-state indicators of various shapes and sizes, and offers a few different rectilinear indicators using LED chips as a light source. One product is called a light bar, and contains 4 LED chips covered by a diffuser material (Figure 22, left). While the product literature and photographs made it seem like it would be a uniform light source, in actuality, when lit, the four areas over the LED chips were visibly brighter under the diffused layer than the regions surrounding the chips. It was clear that the light source had much more than 1% deviation from uniformity and would not be suitable for the project.

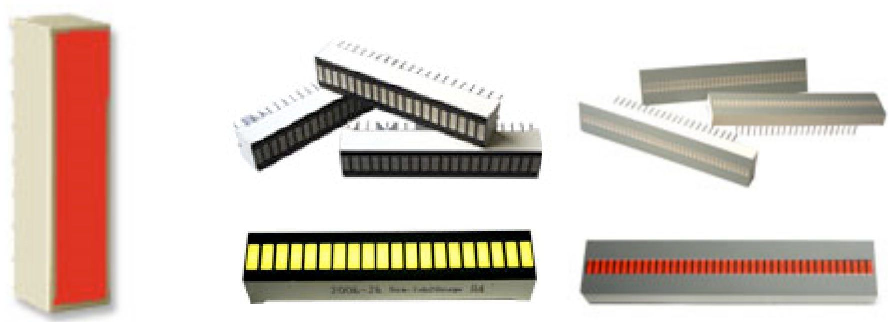

Figure 22 – LED Light Bar (left) & LED Arrays (center and right). (*Not to scale)*

Other available products from Lumex are their LED arrays. These devices contain many more LED chips than the light bars, but organized discretely without a top diffuser. Like the light bar, the 20 segment LED array (Figure 22, center) was too coarse to acheive an overall 1% linearity sensor, and the 40 segment LED array (Figure 22, right) while more uniform, was too long to fit inside our prototype speaker.

Linear Sources – Electroluminescent Wire

Another option that was tested for a light source was using electroluminescent wire (often abbreviated to EL wire). It is made of a thin copper wire core coated in a phosphor, then wrapped by two more extremely fine copper wires. The phosphor coating glows white when a high frequency AC current is applied to the core and outer wires. A colored PVC sleeve can be wrapped around the outside to make the wire glow any color. Since this only removes total light output, testing was performed with an un-tinted white EL wire.

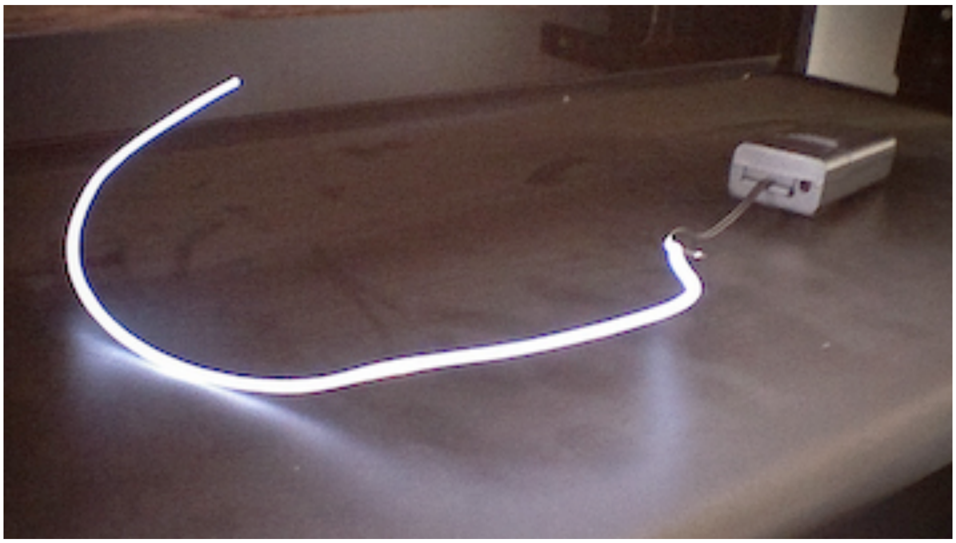

Figure 23 - Illuminated electroluminescent wire

EL wire is very cheap when ordered in reels, and has the advantage that it can be cut to any desired length. While the wire emits plenty of light for it to be seen in dark conditions, it wasn't bright enough to saturate the photocell. Since the EL wire slowly becomes less bright over its lifetime, this would cause the sensor output to drift over a long period of time, requiring some sort of center point calibration. Another problem came from the outer wrapping wires blocking small amounts of light. From a distance, there are no perceptible fluctuations in light along the wire, but since the wire doesn't saturate the photocell, any non-uniformity in the light source would result in a nonlinearity of the sensor output.

Linear Sources – Linear Lasers

At initial glance, line laser light sources appeared to be another viable option. Line lasers are commonly available in numerous consumer laser levels and are heavily used in industrial precision alignment and machine vision applications. In these instances, the most important property for the line is its straightness.

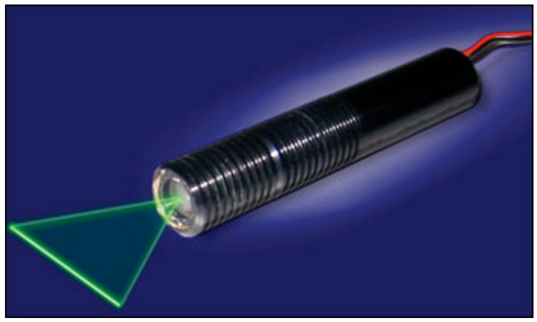

Figure 24 - Line laser diode module

We looked at Lasiris line lasers, since they are one of the few offering non-Gaussian lines [16]. A Gaussian line will have an intensity profile shaped like a Gaussian curve. This is extremely non-uniform and not useful as a line light source for this application. While the product marketing photos make the laser line appear to be perfectly uniform (Figure 24), delving into the intensity profile specifications shows that these lasers vary in intensity across the line by as much as 40% (Figure 25). Lasiris has an option for improving the uniformity to 15%, but even this is too much when requiring 1% position accuracy.

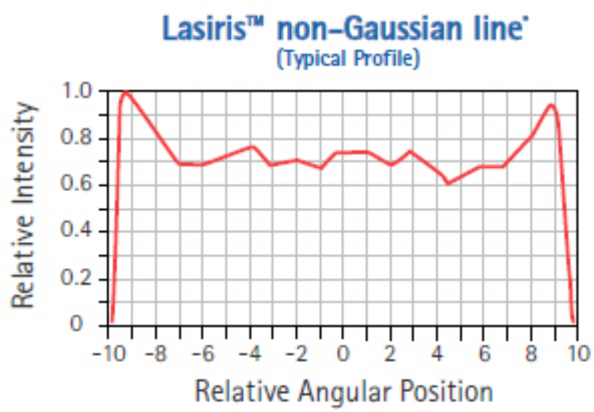

Figure 25 - Line laser diode intensity profile

This non-uniformity is not a problem if the line laser is used for leveling countertops or making crosshairs for a precision alignment device. Those applications depend more on the fact that the line is perfectly straight. But for the purposes of creating a line source, line receiver vane coupled position sensor, that light intensity fluctuation is unacceptable.

Linear Sources – Cold Cathode Fluorescent Lamps (CCFLs)

Compact fluorescent lamps are gas-discharge light sources, which produce their output from a stimulated phosphor coating inside a glass lamp envelope. They are by no means a new technology; with the modern 'hot cathode' fluorescent lamp we're accustomed to using in light sockets and office light fixtures first being patented by General Electric in 1941 [17]. Hot cathode fluorescent lamps have electrodes in the form of a filament that in order to create light, the filaments must be heated from current passing through them.

Cold cathode fluorescent lamps use a different filament design that does not require additional heating. Instead, a much higher voltage is applied to pull electrons out of the filament to ignite the lamp. This simplified electrode design allows for much smaller lamps with reduced complexity of the drive electronics. They also exhibit superior lamp life (around 40,000 hours) when compared to their hot cathode counterparts (around 10,000 hours). Unlike HCFLs, CCFLs also turn on instantly, are very quick to reach full brightness, and can function in a wide variety of temperatures (from 5º C to more than 75º C).

Precursors to the modern fluorescent lamp date back to the invention of the closely related neon lamp in 1910 and 'Moore' tubes containing nitrogen and carbon dioxide gas with a cold cathode in 1895 [18]. But only recently did the technology of miniature CCFL's make great strides in miniaturization and reliability with the advent of the laptop computer for which the CCFLs have typically (until recently with the advent of LED backlights) been the light source for the LCD display.

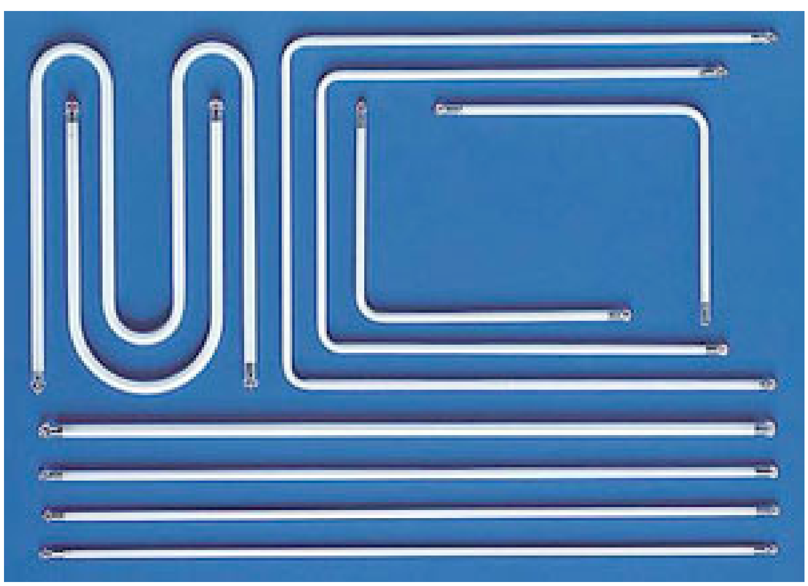

Figure 26 - CCFL's in various shapes and sizes

CCFL's are an ideal light source for a line source, line receiver optical position sensor because, along with the other benefits listed previously, they emit a perfectly uniform light along the center portion of the tube (beginning 0.35 inches from the end of each side). They also generate very little heat, operating at 10º to 15º C above ambient temperature in open air, which is a good then when placing a light source in a small enclosed space such as the voice coil of a speaker. Because of all of these factors, a CCFD was chosen as the light source for prototyping the line source / line receiver optical position sensor design.

A 2 inch length tube (model BF350) made by JKL Components was selected for use in this project because its 1.3 inch uniform light length more than adequately covered the 0.5 inch range of motion of the woofer, yet was still short enough to fit inside the voice coil of the testing speaker. The BXA-12553 inverter was selected because of its simplicity and low cost. Unlike other inverter offerings, it can only power one CCFL, and does not have any dimming capabilities, but those features that weren't necessary for this project.

The lamp and inverter are available in quantities of 100 for $7.45 and $9.37 respectively. Along with the $11.61 cost per solar cell, this brings the total sensor parts cost to $28.43, meeting the client's <$30 price specification.

Feedback Speaker Design and Prototyping

Proof of Concept – Linearity Testing

Using a linear light source and linear receiver with a light vane in theory should result in a linear position sensor, but testing was necessary to confirm that the CCFL and solar cell would in fact meet the 99% linear specification. A test setup was built by mounting the CCFL and photocell into fixed positions on a prototyping board. An opaque light-blocking vane was then coupled to a blade micrometer that was clamped down securely. By turning the wheel on the blade micrometer it moved the vane across the gap between the CCFL and the solar cell, blocking part of the light from reaching the cell (see Figure 27). The micrometer had an accuracy of up to 0.0001 inches, although measurements of this resolution were not necessary. Instead, samples were recorded every 0.025 inches.

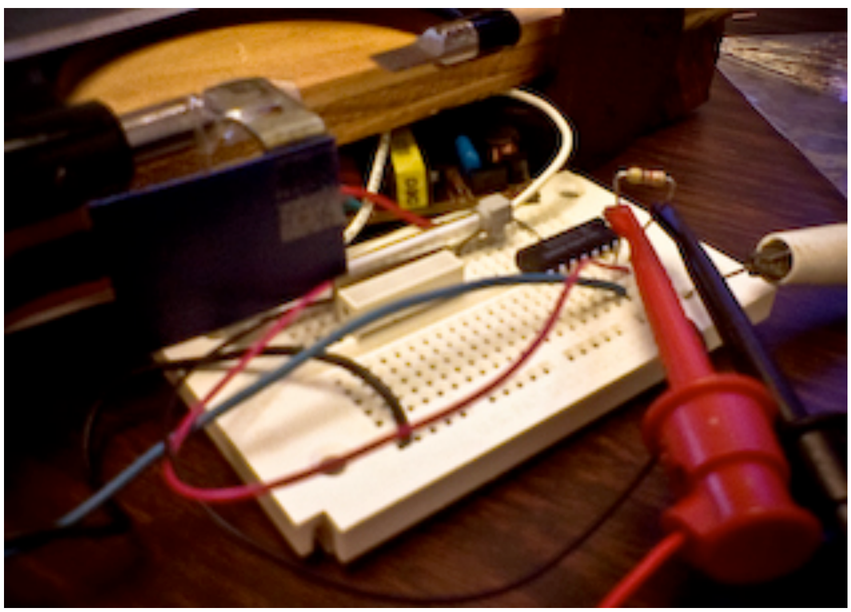

Figure 27 – Linearity proof of concept setup

To accompany this mechanical setup, a simple current to voltage converter op-amp circuit was used to measure the output current of the photocell as a voltage on the multimeter. A single 10K resistor was used as the gain resistor, thus the voltage measurement was proportional to 10,000 times the output current of the photodiode.

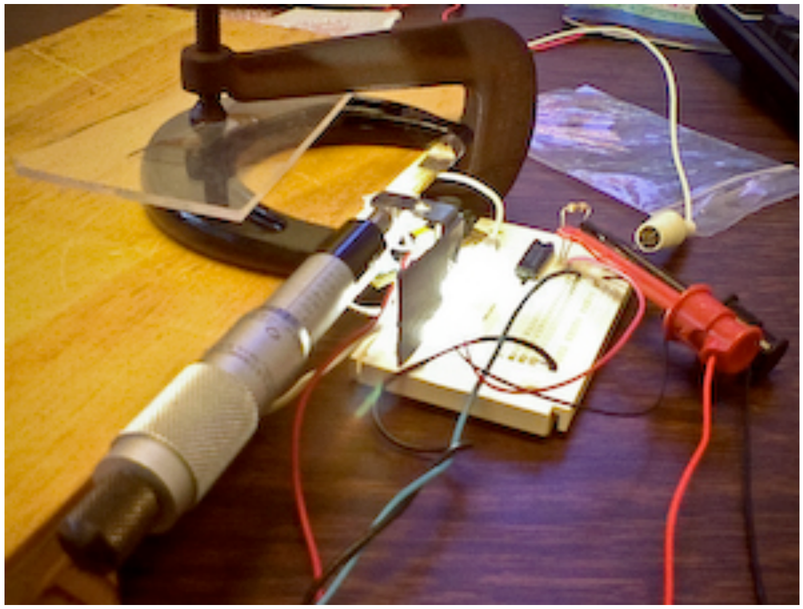

Figure 28 - Linearity proof of concept setup with CCFL lit

Figure 29 shows the results of the CCFL and solar cell with a light vane linearity measurements. There is a center region 0.6 inches long with a linearity of 0.9999. This exceeds the 0.99 linearity requirement, and is 0.1 inches longer than the total 0.5 inches travel of the speaker itself. This extra cushion will allow a bit of leeway in the placement tolerances when the woofer goes into production.

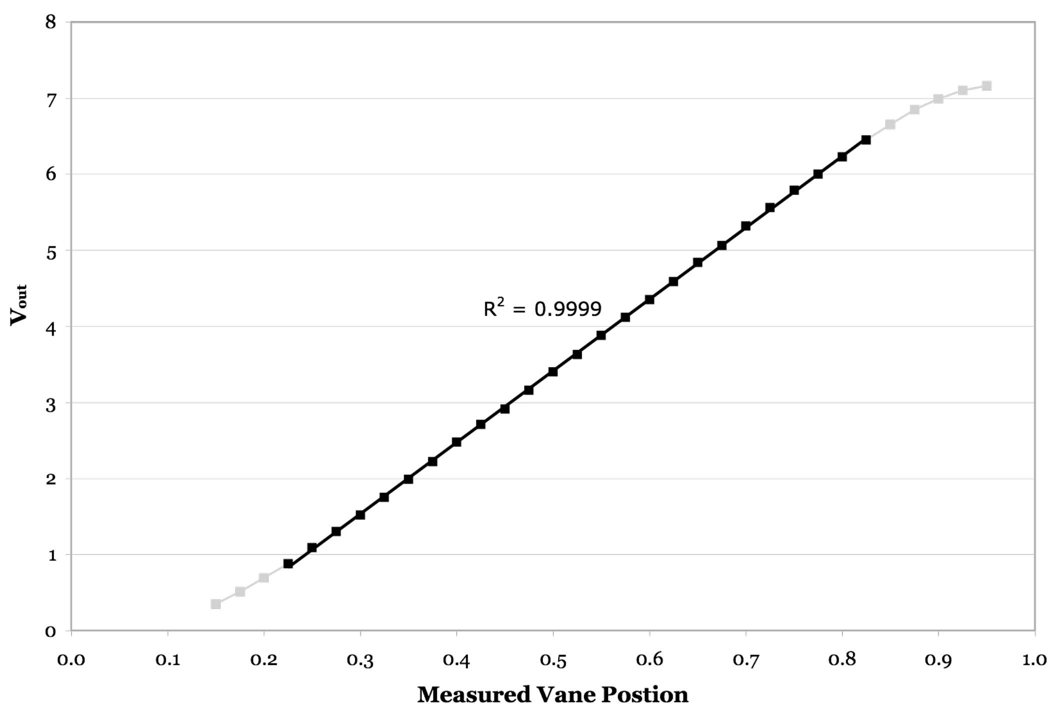

Figure 29 - CCFL and solar cell linearity measurements

First Prototype – Open Baffle

Sensor Mounting Design

Now that the fundamental linearity of the sensor had been confirmed, it was time to design it to fit inside of a speaker. Various mounting schemes were considered as possible ways to place the light and photocell in the speaker, and in the end a simple design as described below was chosen.

The speaker used in this project was a custom made speaker made by Eminence Speaker Corp. It had a vented pole piece, meaning that the pole piece had a hole through the middle with a grate at the bottom, allowing air to pass through. This is not a common feature on a speaker, but is sometimes done with the purpose of helping to keep the voice coil cool. Having the vent allowed wires to be run though the pole piece and out the rear end of the speaker.

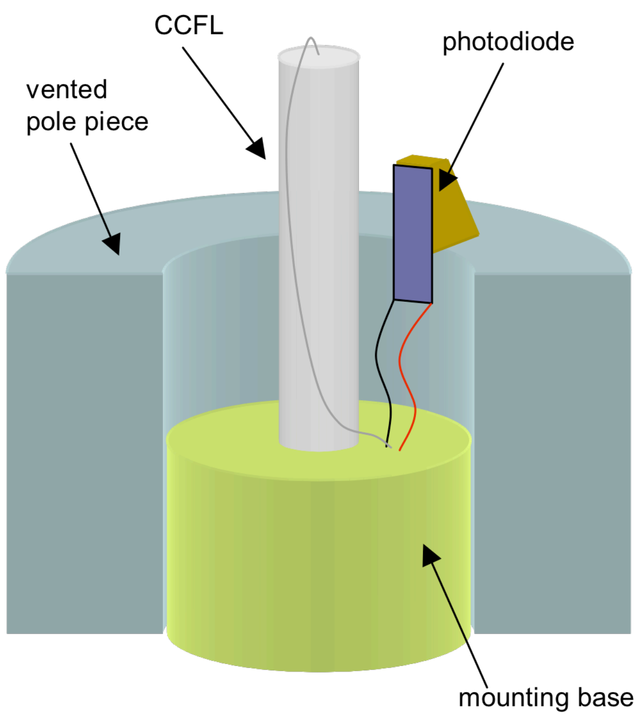

Figure 30 - Placement of parts inside the voice coil

As shown in Figure 30, the CCFL is held in place by a plastic cylindrical mounting base. The CCFL is press fit into a centered blind hole in the base, with a smaller through-hole for the bottom lamp wire to pass through. Another offset hole is used for passing the two photodiode wires and the top lamp wire through to the rear of the speaker. The photodiode itself is attached to the pole piece with a plastic right angle bracket. All parts were simple in design and machined using a conventional mill and lathe, and would be inexpensive to make in larger quantities for mass production. Figure 31 shows these parts assembled inside the speaker before installing the light vane.

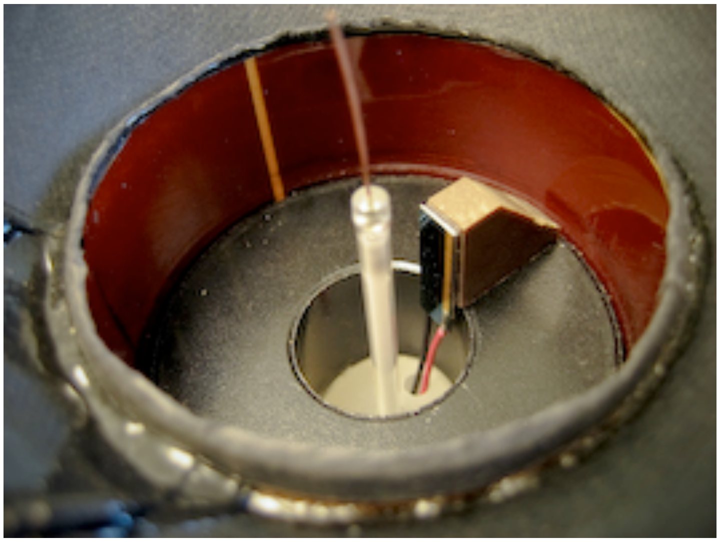

Figure 31 - View of the sensor without the light vane

A opaque light-blocking vane was designed to couple to the voice coil, and fit between the lamp and sensor. Made of black heavy cardstock, it is able to slide up and down through the entire range of motion of the speaker. With no input, the bottom of the light vane rests at the midpoint of the total height of the photocell. As shown in Figure 32, then the speaker moves out, the light vane exposes more of the sensor to the lamp, and when the speaker moves in, the vane exposes less of the sensor to the lamp.

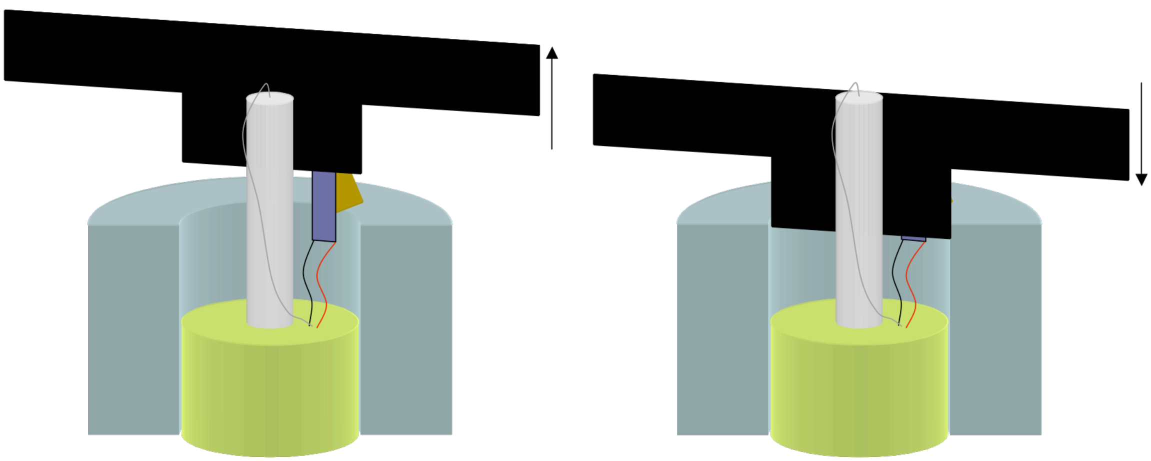

Figure 32 - Vane movement blocking light to photodiode

The vane itself was attached to the voice coil with epoxy. This proved to be adequately strong to withstand long periods of vibration without any signs of wear on the adhesive.

Position Sensing Verification

With the sensors installed inside of the speaker, it was necessary to confirm that the output of the sensor matched the actual position of the speaker. To do so, the speaker was mounted into a custom open-air rig, and a test rig was made with a dial indicator and a magnetic stand to measure the actual speaker position (see Figure 33). The speaker terminals were connected to a DC current source, and a multimeter measured sensor output voltage. In DC, a speaker's position is directly proportional to the current passing through the voice coil, so the speaker could be held at a constant excursion while reading the measured position from both the dial indicator and the sensor.

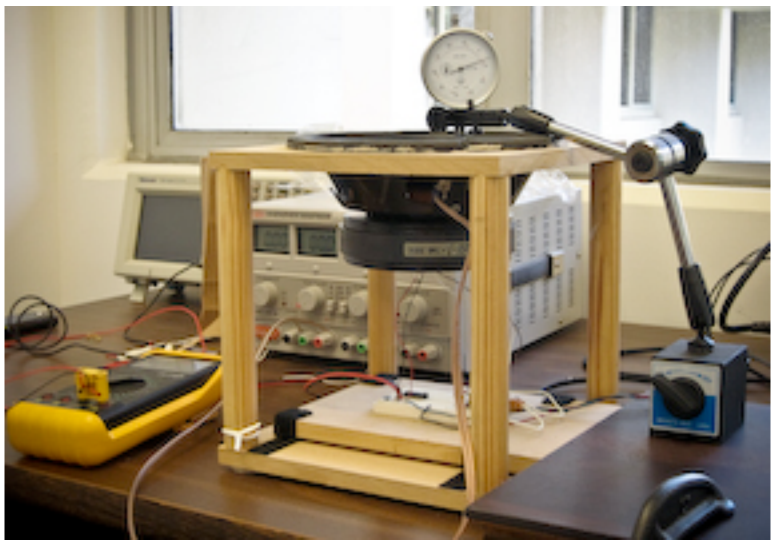

Figure 33 - Dial indicator rig used for directly measuring speaker position

Extra care is required when doing this sort of test. If too much current passes through the speaker for too long of a time, it will heat up the voice coil and melt the laminate covering the voice coil, resulting in permanent speaker damage. Particularly in the high current measurements, it is important to take quick readings, and then reduce the current immediately.

The results of the position testing are shown in Figure 34, with the sensor showing excellent linearity compared to the measured speaker position. It should be noted that due to the limits of excursion of the available dial indicator, only outward excursion could be measured on the speaker. A much more complicated testing configuration could have placed the dial indicator such that it could measure inward excursions as well, but due to the geometrical symmetry of the sensor, it was decided upon that this was not necessary. Future observations confirmed that the sensor's readings of inward motion of the speaker were just as linear as the outward.

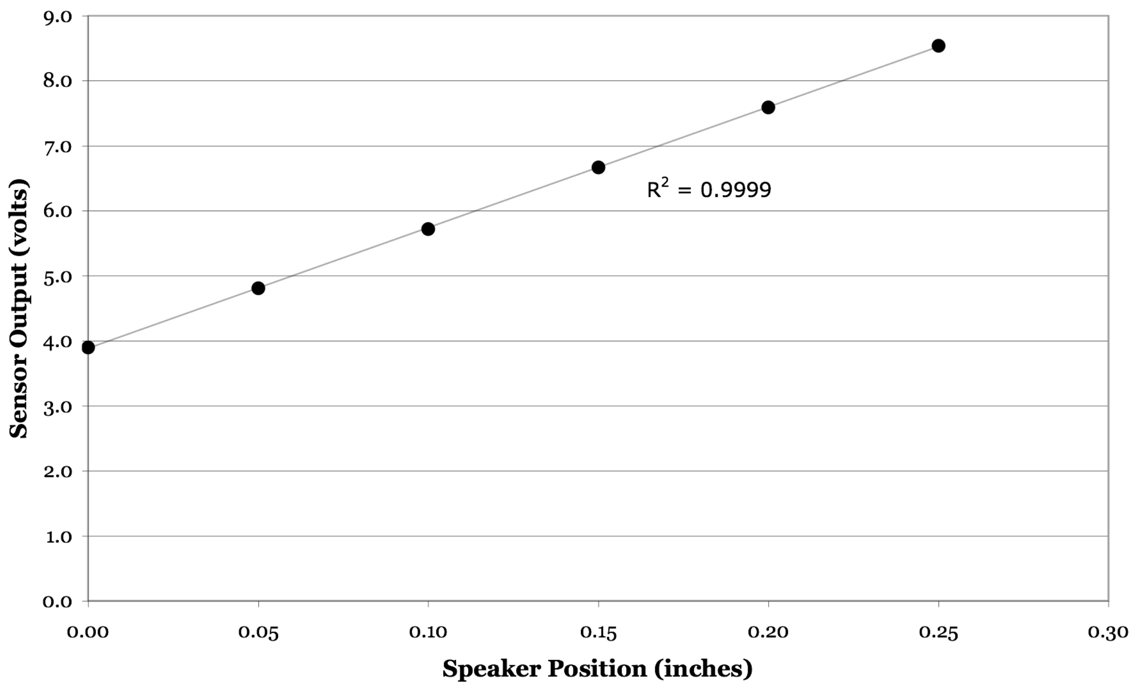

Figure 34 - In-speaker linearity, sensor voltage vs. speaker position

Second Prototype – Infinite Baffle

With the sensor working properly inside the speaker, it was time to put the woofer into a speaker box. The 0.5 cubic foot speaker box was constructed out of 3/8ths inch plywood. Standard good design practices were followed, such as using filling the empty space with batting and sizing the box at proper length/width/height dimensions to minimize internal standing waves [19].

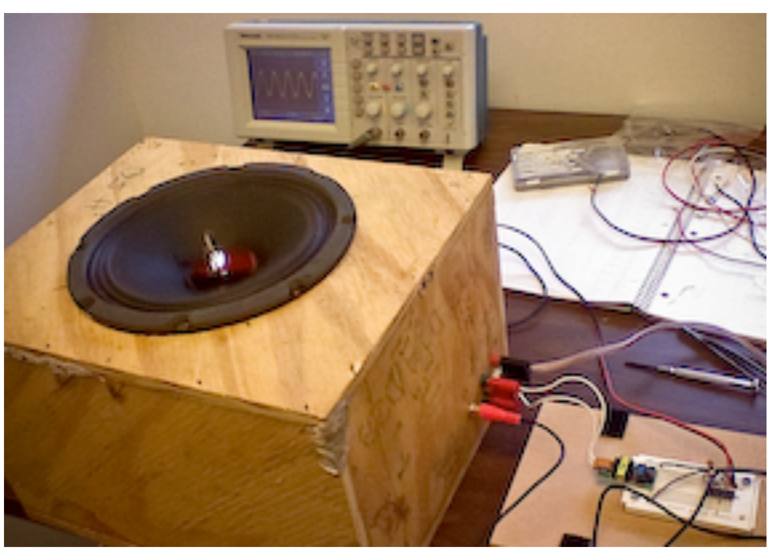

Figure 35 - Woofer in speaker box with oscilloscope showing speaker motion

In addition to the usual audio-in plugs on a speaker box, additional plugs were required for the CCFL power and the output sensor signal. Dual banana plugs were used for audio-in and CCFL power, while a shielded RCA plug was used for the sensor-out. Figure 35 shows the speaker box with the additional plugs, as well as the CCFL inverter and sensor amplifier circuit. Later iterations mounted the inverter circuit card directly onto the speaker box with its own power supply in order to eliminate noise bleeding into the sensor circuitry.

One problem we encountered when the speaker was initially installed into that box was that the CCFL would not light up. The lamp operates at 170 VAC at 25 kHz with a 425 volt spike required to start the lamp. The problem turned out to be that the resistance and capacitance of the wire from the inverter to the lamp was large enough that the high frequency starting signal lost enough voltage that it was insufficient to light the CCFL. This problem was resolved by shortening all wires between the inverter and lamp as much as possible.

Feedback Circuitry

Power Amplifier Modifications

One of the properties of a true position feedback system is that with zero signal, if you press on the speaker, the speaker will push back and will not budge for all of eternity (so long as you don't push so hard that you exceed the power limitations of the amplifier). Accelerometers and velocity sensors have a bandwidth limit such that a feedback system with such sensors would momentarily push back, but then gradually allow the speaker to move inward despite the input signal being at zero.

In order to demonstrate this properly, the amplifier powering the speaker must also extend all the way to DC. No commercial audio amplifiers are designed this way because with no correction, any sort of voltage offset in the signal chain of such an amplifier would result in an offset in the output, which would cause premature speaker distortion.

To demonstrate the DC capabilities of a true position sensor, the audio power amplifier associated with this project was modified to function all the way to DC. While the specific details of the modifications made are beyond the scope of this paper and would require proprietary circuit diagrams to explain, all that is important to know is that such changes were made.

Feedback Circuit Design

The complete and detailed electrical schematic of the feedback circuit used in this project can be found in Figure 40 of Appendix 1 at the end of this document. Figure 36 displays a functional block diagram of the major components of the feedback circuit. Beginning with the audio signal, it is gets summed with the negative feedback signal and sent to a gain stage with a correction bias that re-centers the signal offset to zero volts. This then gets sent to the power amplifier, where the signal is bumped up to speaker levels. The output of the audio amplifier is sent to the speaker, causing it to move. The optical sensor captures the speaker's motion and its output signal travels to an inverting current to voltage amplifier. The inverted output of the current to voltage op-amp is that returns to the adder to be combined with the input audio signal. Along the way though, there is a bypass switch that allows for easy on-off toggling of the feedback.

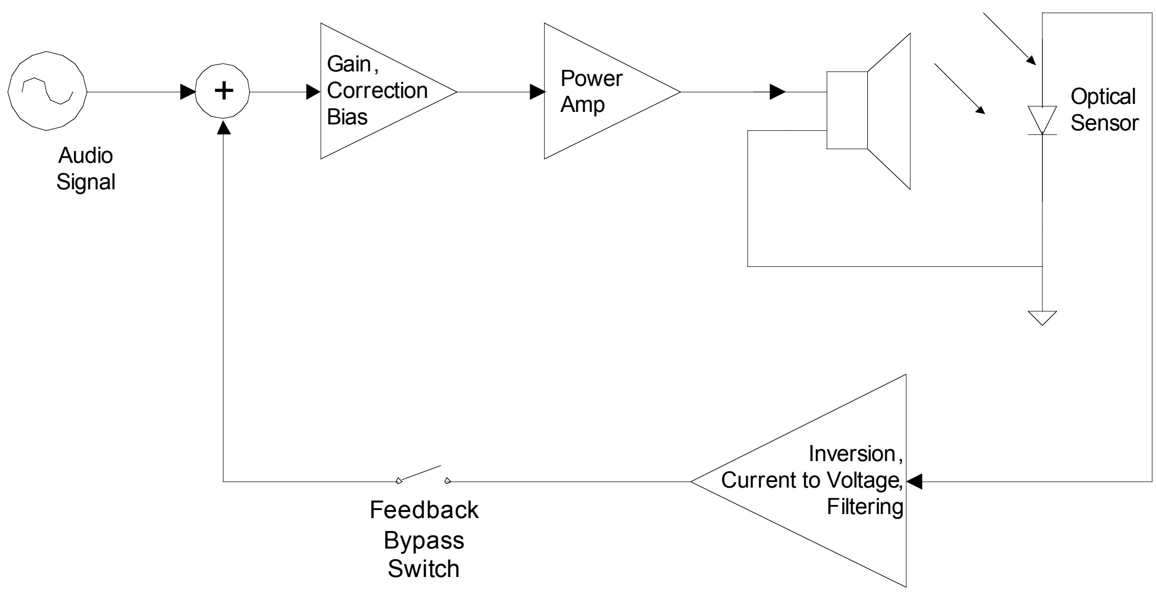

Figure 36 - Circuit Block Diagram for Feedback Woofer System

Speaker Testing and Distortion Measurements

Methodology

With the speaker completely built with a linear position sensor and a feedback circuit implementation, testing began to determine the effectiveness of the negative feedback at reducing the speaker's distortion.

While the position sensor in the woofer is able to track the motion of the voice-coil, this signal alone cannot be used to measure the distortion of the speaker since this would in essence be circular reasoning. An independent measurement of the speaker's motion was required in order to determine these characteristics, which can be accomplished by using a microphone to measure the audio output of the speaker.

Once a measured signal is acquired with a microphone, it can be analyzed with a distortion analyzer to determine the amount of distortion present in signal. A distortion analyzer compares a reference waveform with an input waveform, and displays the percent of distortion present in the input as compared to the reference.

For this project, we used a Rode NT3 condenser microphone connected to an M-Audio Fast Track Pro microphone pre-amplifier. The signal from the pre-amp was routed to a Sound Technology 1710A Distortion Analyzer that also provided the reference sine wave that served as the audio signal for the feedback system. Decibel measurements were read off of a voltmeter with a logarithmic dB scale connected to the microphone pre-amp output, and this was calibrated with a Radio Shack analog dB meter. The microphone remained a fixed 1-foot away from the speaker for all measurements.

Results and Analysis

Open Loop - No Feedback

As expected, the speaker exhibited low distortion at low sound pressure levels (SPLs) while increasing as the volume increased. Figure 37 shows this tendency as measured at 40 Hz and 60 Hz. Overall, the woofer exhibited lower distortion at higher frequencies, and vice versa. As the distortion increased, the measured speaker signal tended to approximate a triangle wave, meaning that the distortion was primarily due to a third order harmonic.

SPL	40 Hz	60 Hz
96 dB	15.0%	1.4%
90 dB	3.6%	0.7%
84 dB	1.9%	0.4%
78 dB	1.0%	0.6%

Figure 37 - Open loop distortion at various sound pressure levels

Closed Loop – With Feedback

When negative feedback was applied to the system, keeping all other things consistent, the output volume of the speaker decreased. This was because we were adding a negative sinusoidal wave to a positive sinusoidal wave, resulting in a net reduction in wave amplitude. To measure the quantity of feedback in a closed loop system, measure the output level from the open loop state, and compare it to the output level in the closed loop state. The difference is amount of feedback, measured in decibels. In order to compare the amount of distortion in open loop vs. closed loop, one must adjust the input signal level when switching between one and the other such that they both deliver the same SPL.

While measuring distortion of closed loop vs. open loop operation, we quickly found that at high SPLs, the distortion increased with feedback. These alarming results warranted further investigation.

On a loudspeaker, across the resonant frequency there is a 180° phase shift. The shift begins slightly before the resonance, and at the resonance point there is exactly a 90° phase difference between the input and the output of the speaker. Operating a feedback system across such a phase shift would result in regions of unstable positive feedback, so it's important to stay on only one side of the resonance. Before reaching the resonance point, there comes a point where there is a 60° phase shift between the input and output of the speaker (equivalent to a 120° phase difference between the two added signals in the feedback loop). At this point, the magnitude of output signal in open loop vs. closed loop is exactly the same. No matter how much feedback gain, the net feedback is 0 dB.

To ensure that the feedback circuit was not adding excessive noise to the system, causing the increase in distortion, we measured the distortion at the 60° point and found that the feedback only added 0.5% distortion at that frequency. This meant that the circuitry was adding very little noise, and did not account for the much larger amounts of distortion we were measuring when adding feedback (up to 30% at 30 Hz at 89dB with 6dB of negative feedback).

Voice Coil Movement vs. Speaker Movement

Earlier linearity testing had verified that the sensor output matched the actual position of the voice coil, to which the light vane was attached. The results of the distortion analysis were pointing toward the conclusion that there was a disconnect between the motion of the voice coil driven by the input signal and that of the speaker which pushes the air to create sound.

An oscilloscope was set up to simultaneously display the speaker output as measured by a microphone on top half of the screen and the sensor output as measured by the position sensor on the bottom half of the screen. All oscilloscope figures on the following pages retain this configuration.

Figure 38 shows the comparison of the microphone measurement (top) versus the position sensor measurement (bottom) for a 30 Hz sine wave with amplitude of 8 VAC being sent to the woofer. This produced 93 dB SPL at 1 foot from the speaker, which is fairly loud for the 8 inch woofer. At that level, the voice coil was starting to exhibit some distortion in the form of an asymmetry of the sine wave. Asymmetrical distortion such as this is an indicator of 2^{nd} order harmonic distortion, and this asymmetry also appeared in the measured output measured with the microphone.

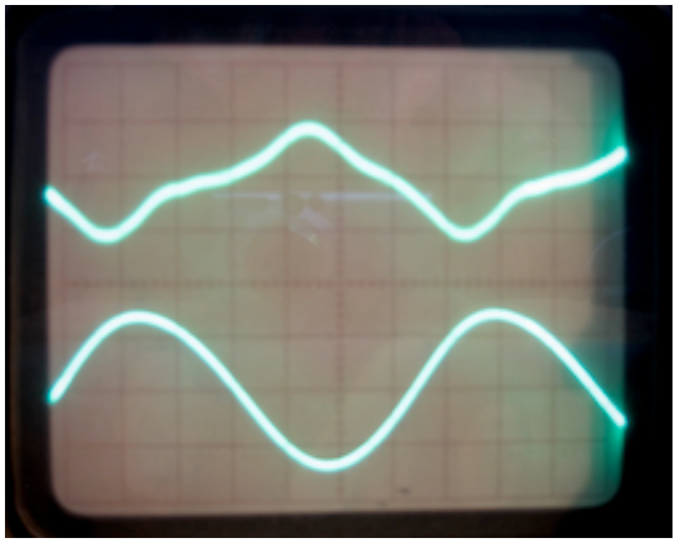

Figure 38 - Speaker vs. Sensor Output (30 Hz, 8 VAC, 5 ms horizontal scale)

In addition, the microphone waveform had some humps that occur halfway between the peeks. The peaks themselves were also pointier than what would be experienced from a pure 30 Hz sine wave. This indicated the presence of a 3^{rd} order harmonic distortion. That distortion was not present in the position sensor signal, meaning that the voice coil was not experiencing 3^{rd} order harmonics. Overall, the position sensor signal contained 9% THD, while the microphone signal contained 15% distortion.

Figure 39 shows a more extreme example of the distortion discrepancy. In that case, the woofer received a 20 Hz sine wave at 10 VAC. The voice coil displayed the expected 2^{nd} order distortions (12% overall), while the speaker output contained equivalent 2^{nd} order distortions but much stronger 3^{rd} order distortions (55% overall).

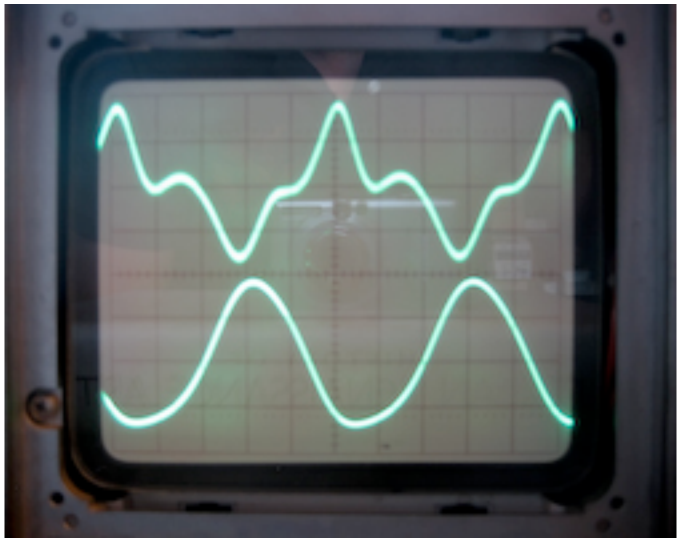

Figure 39 - Speaker vs. Sensor Output (20 Hz, 10 VAC, 10 ms horizontal scale)

From these measurements, it was clear that the speaker cone was exhibiting strong resonance modes. Rather than traveling with ideal “pistonic” motion, the speaker was flexing out of sync with the motion of the voice coil [21]. Also known as cone breakup, this phenomenon can be measured and visualized with the use of laser scanning equipment [20].

The presence of such strong cone breakup made the feedback circuit unable to correct the strong distortions present in this particular woofer. Unable to detect the resonant modes occurring in the speaker cone, the position sensor could only correct for distortion imparted from fringe magnetic fields acting on the voice coil.

While the prevailing distortion of this woofer came from the resonance modes as a result of the cone flexing, even measuring position at some point on the cone surface rather than the voice coil would still not provide the proper feedback signal to mitigate distortion. Cone breakup is made up of multiple dimensions of flexing, including radial and concentric cone modes, so the distribution of flexing varies throughout the surface of the speaker cone. Finding a way to mitigate the cone breakup would be essential in order to make the feedback system effective at reducing distortion.

Conclusions and Future Work

This project set out to design and implement an inexpensive position sensor that could accurately track the motion of a subwoofer speaker. Various sensing methodologies were explored, and a variety of sensor components were tested for linearity during the design process. A viable line-source, line-receiver design consisting of a miniature cold cathode fluorescent lamp and a photodiode was chosen and engineered for simple manufacturability to be installed into a conventional 8-inch woofer loudspeaker. Associated electronics for a closed loop negative feedback control system were designed, and a working prototype was successfully built and tested.

During the testing, it was found that cone breakup was the dominating source of feedback for the particular driver used, and that a different speaker cone design would be required in order to get the full distortion reduction benefits of position feedback control.

The Eminence speaker used in this project was chosen due to its relatively large voice coil for a woofer of its size, which allowed sensor components to fit inside, for the presence of a vented pole piece which allowed wires to travel from inside the voice coil out the back of the speaker, and for some of its Thiele-Small parameters allowing it to fit in a small enclosure without any major spikes in the frequency response. The woofer's shallow cone geometry and paper cone material made it susceptible to strong resonance modes that could not be controlled with feedback.

Subsequent designs will have take into account the cone material and geometry to eliminate cone breakup. Cone geometry has been shown to have a major effect on the presence of resonance modes [22], so speaker cone with deeper conical geometry, or advanced cone geometry such as a bent neck Y-cone should be considered.

Cone material also has a major effect on the presence of resonance modes. If the cone geometry is weak, then choosing a stiffer material will reduce some of the cone breakup. Aluminum is stiffer than paper, but also has no inherent damping, so any resonances that appear despite the higher rigidity will more evident.

In summary, cone breakup can be mitigated by either using a soft material with a high amount of damping (such as Kevlar) used in conjunction with strong cone geometry, or by choosing a material rigid enough that resonance modes do not have the opportunity to materialize no matter what the geometry.

Sandwich panels take advantage of mechanical geometry to convert flexing moments into compression and tensile forces. This results in materials that are extremely rigid yet exceptionally lightweight, making them ideal for use as a speaker cone. The use of such materials is prevalent in the construction of airplane body parts and ship's hulls, but is just starting to appear in speaker cone designs [23, 24]. Further work into harnessing sandwich panels may yield woofers that completely eliminate all cone resonances.

Acknowledgements

I would like to thank Roger Modjeski for sharing with me his vast knowledge of audio while working on this project. I'd also like to thank my committee members Stephen Pope, Matthew Turk, Curtis Roads, and JoAnn Kuchera-Morin for their advice and guidance. More thanks go to Andy Weinberg, Nelson Bednersh, and Michael Schmitt for providing the use of their machine shop and wood shop for construction of numerous parts on this project. And of course, my eternal gratitude to my parents for their love and support in all aspects of my life.

Appendix 1 – Feedback Circuit Diagram

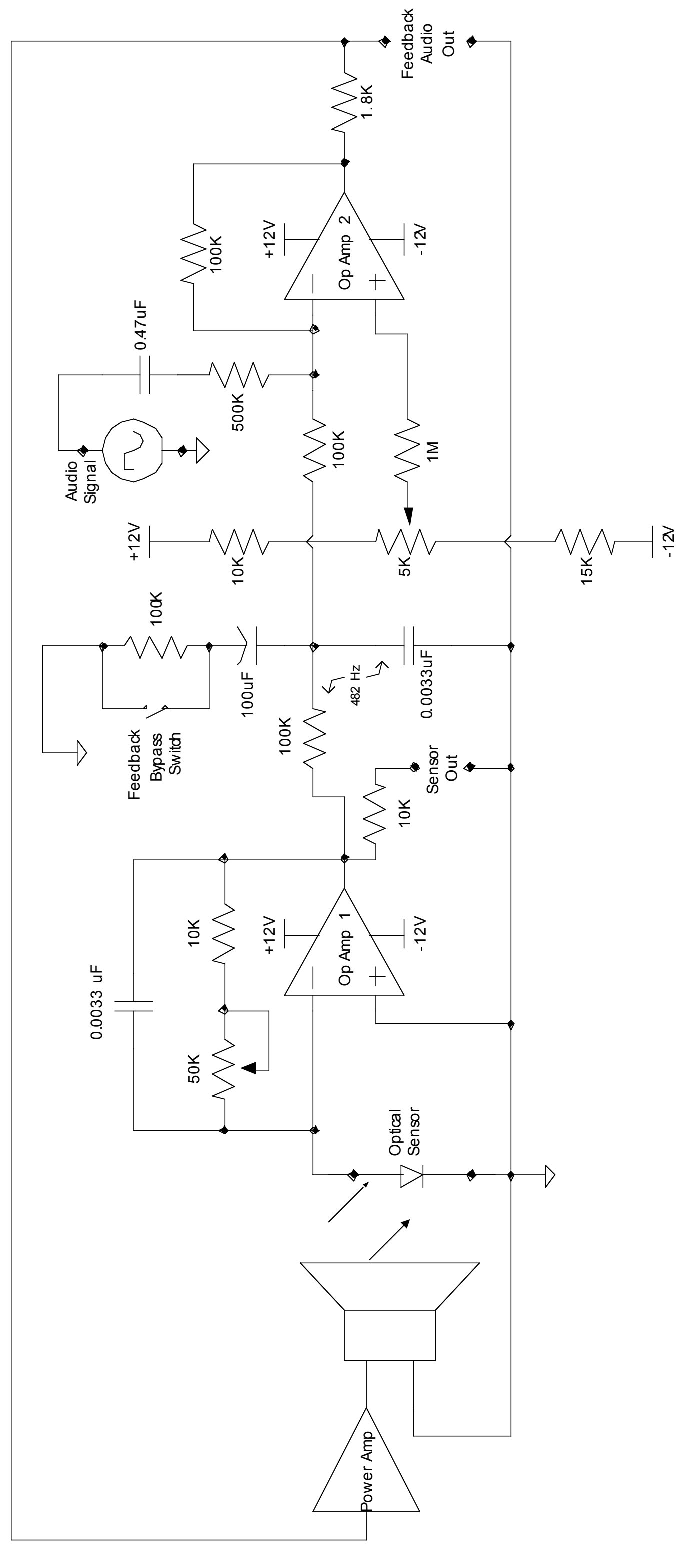

Figure 40 - Circuit Diagram for Feedback Woofer System

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