WEB SPREADING MEASUREMENTS USING PHOTOELECTRIC SENSORS

By

FITOURI HNAINIA

Bachelor of science

Oklahoma State University

Stillwater, Oklahoma

1990

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillement of
the requirements of
the Degree of
MASTER OF SCIENCE
May, 1993

OKLAHOMA STATE UNIVERSITY

WEB SPREADING MEASUREMENTS USING
PHOTOELECTRIC SENSORS

Thesis Approved:

Thesis Advisor

Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to thank the school of Mechanical and Aerospace Engineering for all the support and encouragement they gave me throughout my graduate and undergraduate programs at Oklahoma State University. In particular, I would like to give my sincere thanks to my advisor, Dr. R. Delahoussaye, for his advice and support that I couldn't do without and for his patience and understanding especially at times when things weren't going well for me. I also would like to express my gratitude to Dr. Keith Good who offered me invaluable help and support whenever I needed it the most. I also would like to thank all my committee members, Dr. Richard Lowery, Dr. Edwardo Misawa, and Dr. Price for their help and assistance.

Special thanks to Mr. John Wanou at FIFE Corporation, the maker of the SE-11 photoelectric sensor, and to Mr. Jerry Owens at the Applied Roller Technology Corporation for their technical advice.

I would like to dedicate this work to my father, Salah, and my mother, Aisha.

TABLE OF CONTENTS

LIST OF TABLES

Table — Page

Table		Page

Table Page

LIST OF FIGURES

Figure | Page

CHAPTER I

INTRODUCTION

Introduction

Engineering is a profession that is significantly dependent upon measurements. Without measuring devices, such as rulers, micrometers, gages etc. engineers would be left with guesses, speculations, and mathematical equations lacking any physical meaning. In any experimental work that involves a measuring process the accuracy and validity of the results and conclusions is dependent upon the "goodness" of the various measurements conducted within the experiment. However, a measurement is as good as its measuring device. Although it might seem easy most measuring devices have inherited some limitations and difficulties in them. Especially when applied in complex systems which have very limited space such as web handling lines.

Measurement is the basis for all engineering test work. Engineers for many years have put much effort into increasing the sensitivity, utility, and most of all the accuracy of their method of measurement. The measurements made in engineering test work depend on the type of specimen being tested as well as the type of information desired. However, every measurement is, by nature, in error no matter what measuring device is being used. Therefore, for the measurement to be meaningful, the nature and magnitude of the error should be known.

Web handling is a broad field of study. Although, much research has been conducted on the subject throughout the last few decades, many questions regarding the subject are yet to be answered.

Web handling deals with the process of moving and controlling webs while various operations are done to them. Spreading is one of these operations. It is a critical factor in controlling the transportation of films as they pass over rollers. Web wrinkles, "which are out of plane deformations of web as it moves over rollers", can undoubtedly result in quality reduction in winders. Spreading is the most effective way of wrinkle removal.

Nowadays, web applications require precision more than ever before. Precision in loads, stresses, and position of the web in both machine and cross machine directions. However, locating the exact position of a web edge or measuring its displacements to high degree of accuracy, 1/10,000 of an inch for instance, is no easy task especially across a vibrating web moving at high speeds.

As a web runs across a spreading curved axis roller it gets stretched in the cross machine direction. This stretch is usually a small change in the web's width. This change is so small that too few people have successfully quantified it. The latest attempt to measure web edge displacement was made in late 1990 by Taetcheol[2] who used a laser-based position detector. Taetcheol's experiment will be briefly discussed in chapter II.

In my experiment, I attempt to use FIFE's SE - 11 modulated light sensor as shown in Figure 1. This "state of the art mini-sensor" has several advantages: It's

- precise
- small
- compact
- light
- temperature stable
- ambient light (including sun light) insensitive.

All these properties increase its web application especially where space is limited and high precision is desired.

In order to use the sensor in actual edge displacement measurements, it had to be calibrated. A high precision micrometer (0.0001 inches) was required since the desired edge displacements are in the order of few thousands of an inch. However, since the output intensity was dependent on the web's transparency(degree of opaqueness), each sensor has to be calibrated for every web material used in the experiment.

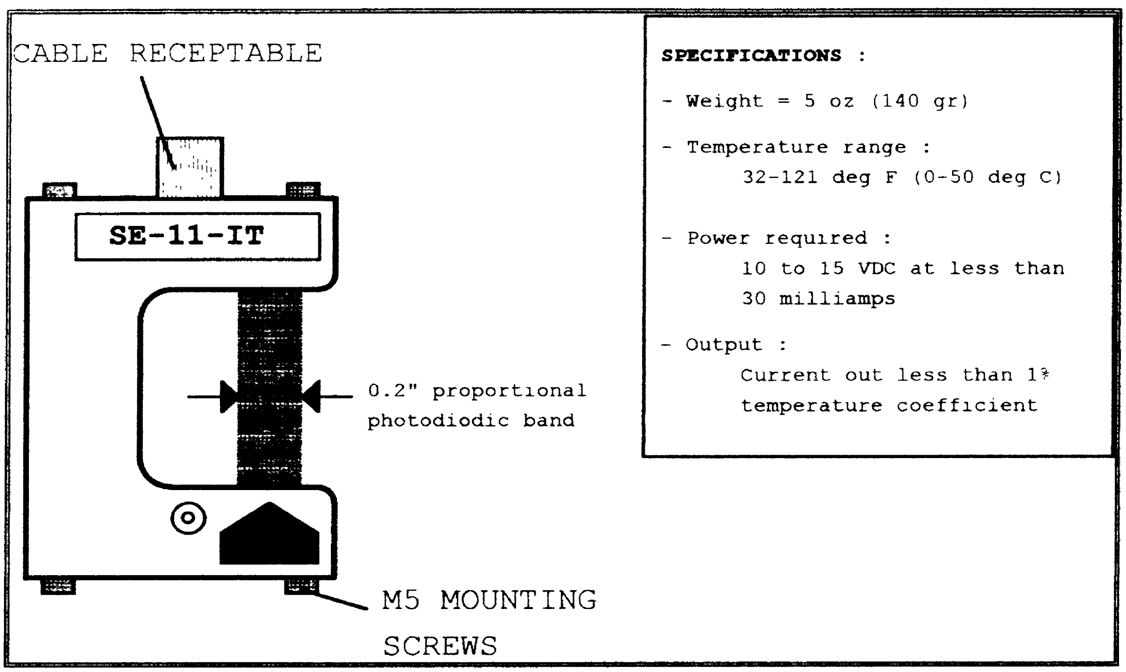

Figure 1. FIFE's SE-11 Modulated Light Sensor

Objectives

The primary objective of this experiment is to calibrate two photoelectric sensors and use them to measure web edge displacements. These displacements are in the order of few thousands of an inch under the experimental conditions that will be described in a later section.

Another objective of this work is to verify a theoretical model written by Delahoussaye[1]. The model gives displacement predictions given experimental conditions.

CHAPTER II

LITERATURE SURVEY

Literature

Displacement Measurements

Moore[6] said that if a length can be seen by an observer, it can be measured directly. A length, or a change in length, is simply the distance between two reference points. Howard[3] said that the average human eye can only discern small lengths of the order of 1/200 inch (0.005 inch) but no smaller. Therefore, for higher precision the human eye and direct measurement is of no help.

In his 1961 edition of "Mechanical Measurements", Beckwith[5] classifies displacement measuring devices into four different groups according to their resolution. First, the low-resolution devices (up to 1/100 inch). They include calipers, dividers, as well as surface and thickness gauges. Second, medium-resolution devices (up to 1/10,000 inch). These include various forms of micrometers, ordinary, inside, depth, screw, thread, etc., used directly or with the assistance of gauges. They also include dial indicators, measuring microscopes, specific-purpose gauges, as well as vernier instruments. Third is the high-resolution devices (to a few micro inches). These are gauge blocks used directly or with the assistance of some form of comparators. Finally, The super-resolution devices (to fractions of micro inches). Various forms of interferometers used with special light sources. Fife's SE-11 sensor is one type of interferometer.

Web Edge Displacement

Web edge displacement is a very important part in many web control applications. However, this parameter, is not easy to compute especially to high accuracy (1/10,000 of an inch for instance). The fact is that throughout the years, it hasn't been easy to accurately measure edge displacement. The reasons for this include:

- The inefficiency of the existent measuring devices
- The limited space available around spreading devices

- The magnitude of the spreading which could be too small to measure

This definitely explains the lack of research done in this field. As a matter of fact most of the work done regarding this matter has been conducted within the last few decades.

The most interesting work that I encountered belongs to Taecheol[2] who tried to finish the work initiated by Delahoussaye[1]. Taecheol's work, which could be the latest work conducted on this subject, depends on the use of an He-Ne laser, a cylindrical glass rod, a one-directional measurement detector, and a 0.01 mm-resolution micrometer to predict the web edge displacement. A laser beam ray of 0.65 mm diameter emitted by the He-Ne laser is spread into a line of light using the cylindrical glass rod. This line of light falls on the active area of the detector. The micrometer interrupting the spread light of the laser beam allows the measurement of the absolute position of the laser beam simply by moving the spindle of the micrometer. Figure 2 shows the set up used by Taecheol. Taecheol's work resulted in displacements ranging from 0.00022 to 0.00050 inches which is far behind the needed 0.0001 inch accuracy.

One of the major problems Taecheol[2] faced was the sensitivity of the detector to all sorts of surrounding lights, including ambient light. Taecheol tried to minimize this effect by conducting his tests under dark conditions. Another major problem was the voltage driftage especially if a lot of time was given between consecutive test measurements. This was due to the thermal expansion of the different components in the experimental setup.

Delahoussaye[1], in the other hand, who started Taecheol's laser-detector experiment, also tried using an optical device, Bausch and Lomb Super Gauge no. 38.21.32. Although the device was marked to indicate 0.001 inches only, it was possible to estimate web edge locations to the nearest 0.00025 inches. This was much better than the results he obtained using the laser beam detector setup.

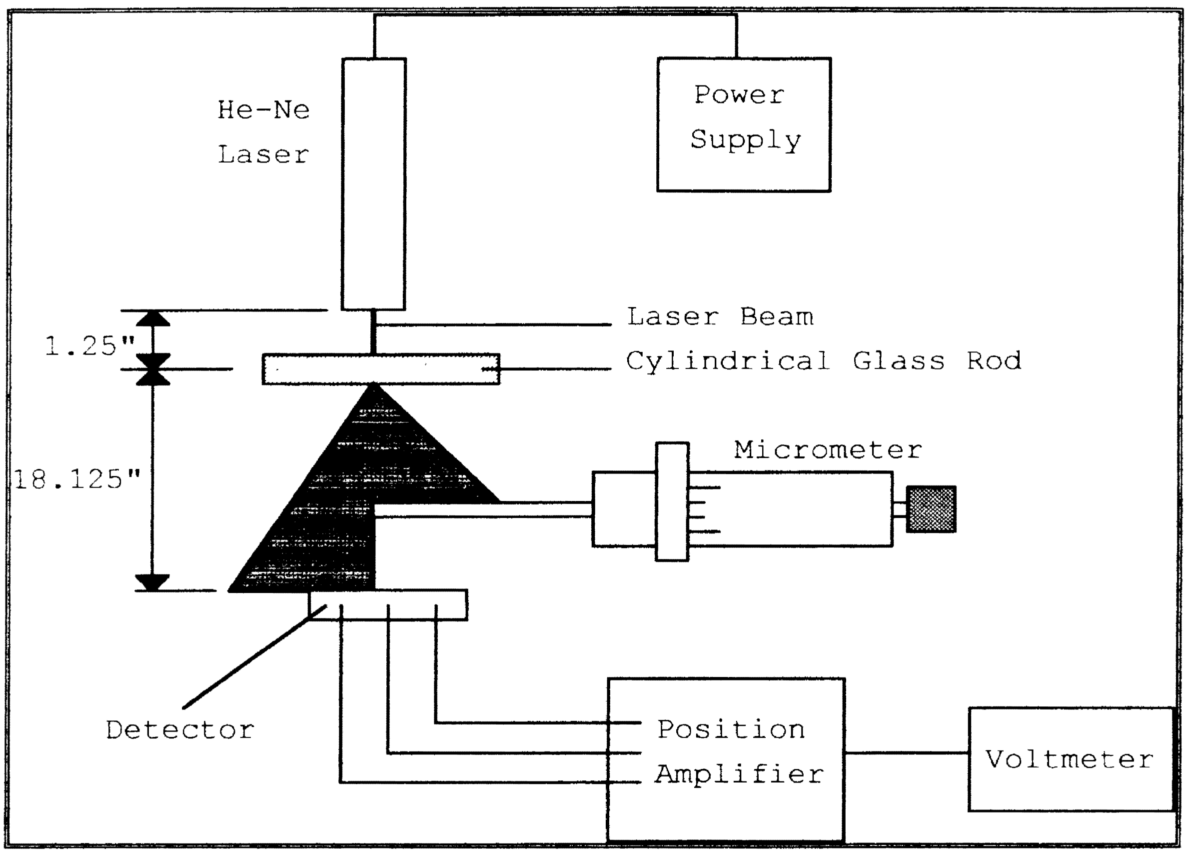

Figure 2. Taecheol's Manual Experimental Setup Of a Position Measurement System

FIFE'S SE-11-IT Modulated Light Sensor

Description Of The FIFE Sensor

Web edge sensing has always been a problem especially for transparent film webs. Different types of sensors, pneumatic, ultrasonic, optical and other sensors have been used but they all have their own problems and difficulties. For instance, as Gronquist[7] mentioned, in transparent film applications, the typical usable optical sensor output can be as low as 10% of that obtained from a normal opaque web. Therefore, if a web were 10% opaque a thermal drift of 5% would become 50% of the usable output signal due to the fact that any error or thermal drift will be amplified as it moves through the system electronics along with the control change.

All these problem and many others have led to the development, using modulated infrared (IR), of a mini sensor, the SE-11 sensor, to be used with most types of webs. This high precision mini-sensor was designed using modern design techniques and Surface Mount Technology (SMT).

Fife's SE-11-IT modulated light sensor is one of the smallest sensors available in today's market. Its compact size, light weight, temperature stability, insensitivity to ambient light (including sunlight), and precision operation make it ideal for many web applications, especially where space is very limited.

Operation Of The Sensor

Fife's SE-11 modulated light sensor, as described by Fife[9], measures the lateral position of the guided material photo electrically as shown in figure 3. The sensor uses a focused uniform curtain of modulated infrared (IR) light. The modulation is sensed and determines the position of the web. The control range or proportional band is 0.2 inches (5 mm) and the sensor is unaffected by plane level (H) changes.

The infrared emitter operates at approximately 950 nanometers and is modulated at 5 KHz. This new mini-sensor utilizes advanced circuitry, which is implemented using Surface Mount Technology (SMT), resulting in the smallest and most reliable sensor.

The sensor's output is proportional to the web position with respect to the photoelectric ray. In other words, it's proportional to the area of the photoelectric band covered or blocked by the web. For the SE-11-IT the output is a current at less than 1% temperature coefficient. The sensor will output 10 mA if nothing is blocking the photoelectric band and 0 mA if the band is completely blocked. This of course when used with an ideal web i.e. a 100% non transparent web relative to the sensor's photoelectric ray.

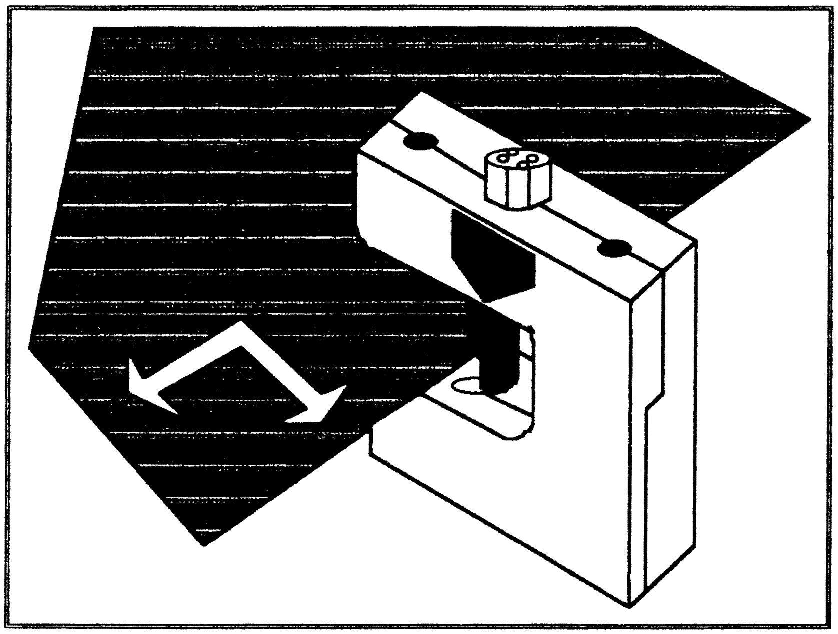

Figure 3. Modulated light Sensor
and Web position

The sensor requires a power supply of 10 to 15 VDC at less than 30 milliamps.

In my experiment, a 500 Ohm resistance is used to convert the output to volts instead. The material experimented is dark brownish polyethylene with about 70% degree of opaqueness. The final output voltage ranged from 0 to 5.0 volts.

Spreader Rollers

Description

A standard spreader roller or curved axis roller is shown in figure 4. It has a curved axis shaft that is formed to a uniform radius. Its main use is to provide spreading in a web with zero spreading at the center and increased spreading as we move towards the edges of the web. Although it can be used with a wide variety of materials, a standard spreader roller is usually limited to constant-width webs and webs of the same material.

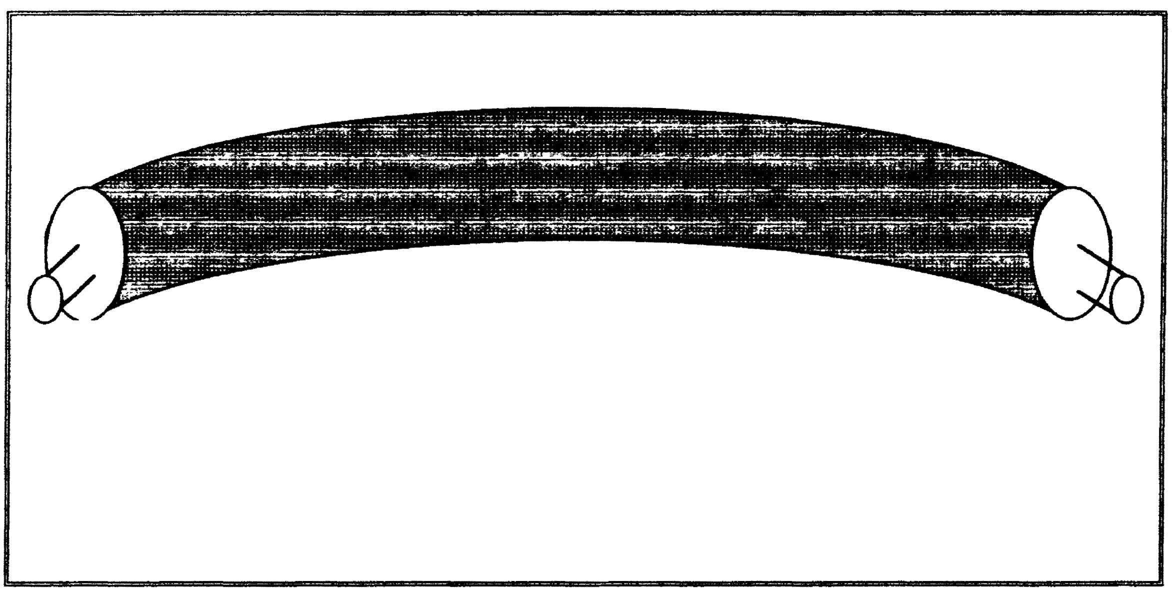

Figure 4. A standard Curved Axis Roller

A spreader roller can also be used in many other applications on a given web process depending on how and where it is placed within the web. Arteh[8] says that these various uses can cause different effects which can be categorized as follows:

-Removing wrinkles or smoothing
-web expanding
-slit separating
-warp spacing
-tension equalizing for webs to be coated or laminated
-etc.

All of these applications require specific bits of information in order to get the correct selection of the required roller and the method of installation.

How does spreading occur ?

As a continuous sheet of web travels over a straight roll, with a sufficient wrap angle, the web tends to travel over the roll at right angles to the axis of the roll as shown in figure 5. If this straight roll is cocked or angled, the effect is the same. The web travels over the roll on a path perpendicular to the roll axis and is therefore taken to a new path

,figure 6 shows this effect. However, if we substitute a curved axis roll for the straight roll, figure 7, interesting results happen. At the center, the web travels straight across, but at points away from the center the web tends to turn and move outward. The result is an even smoothing of the web.

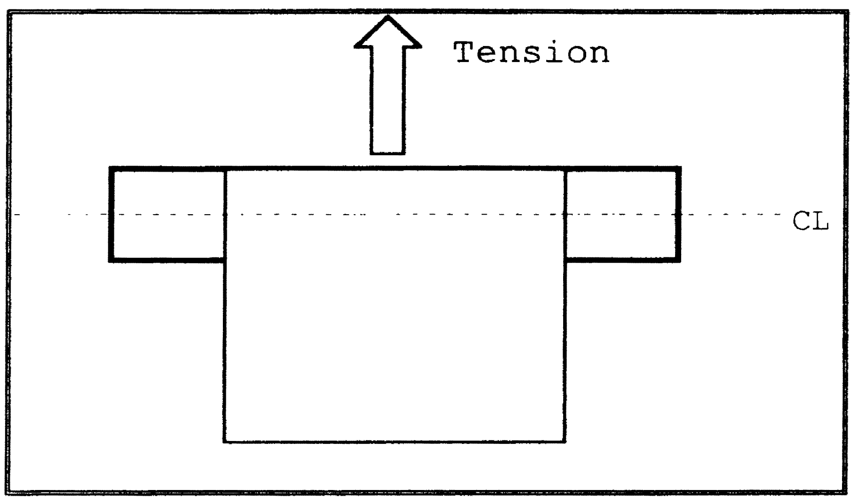

Figure 5. Web Moving Over a Cylindrical Roller

Figure 8 shows possible roller orientations for normal and special web conditions as described by Artech[8]. Figure 8(a) shows the standard orientation which is used with uniform webs with no sagging effects. Figure 8(b) is the orientation that compensates for a baggy center of web. And figure 8(c) shows the preferred orientation for sagging web edges.

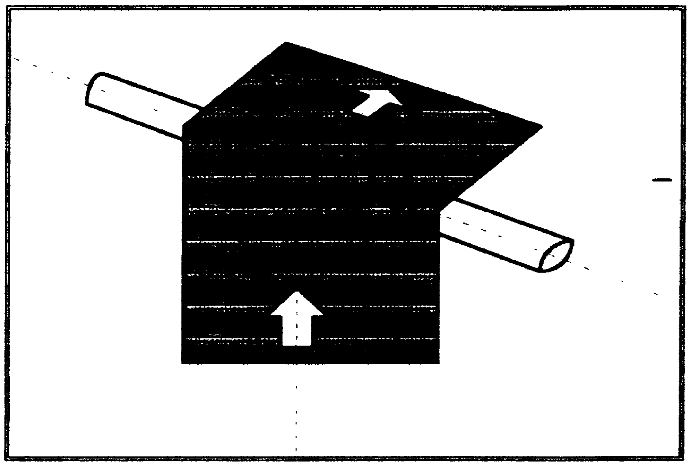

Figure 6. Angled Straight Roller (Obey Normal Entry Rule)

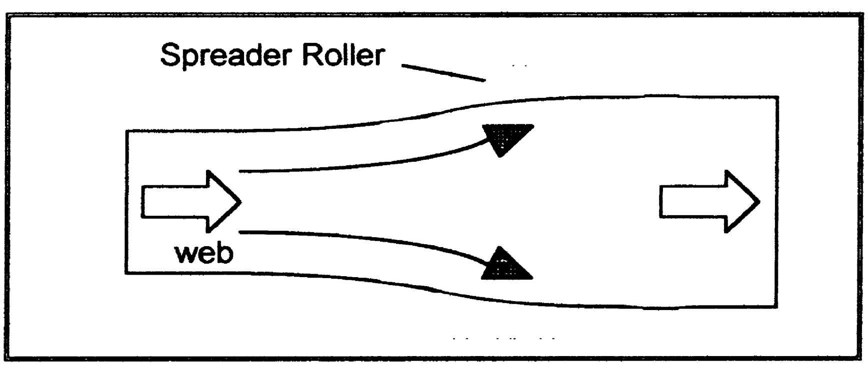

Figure 7. Effects of a Spreader Roller

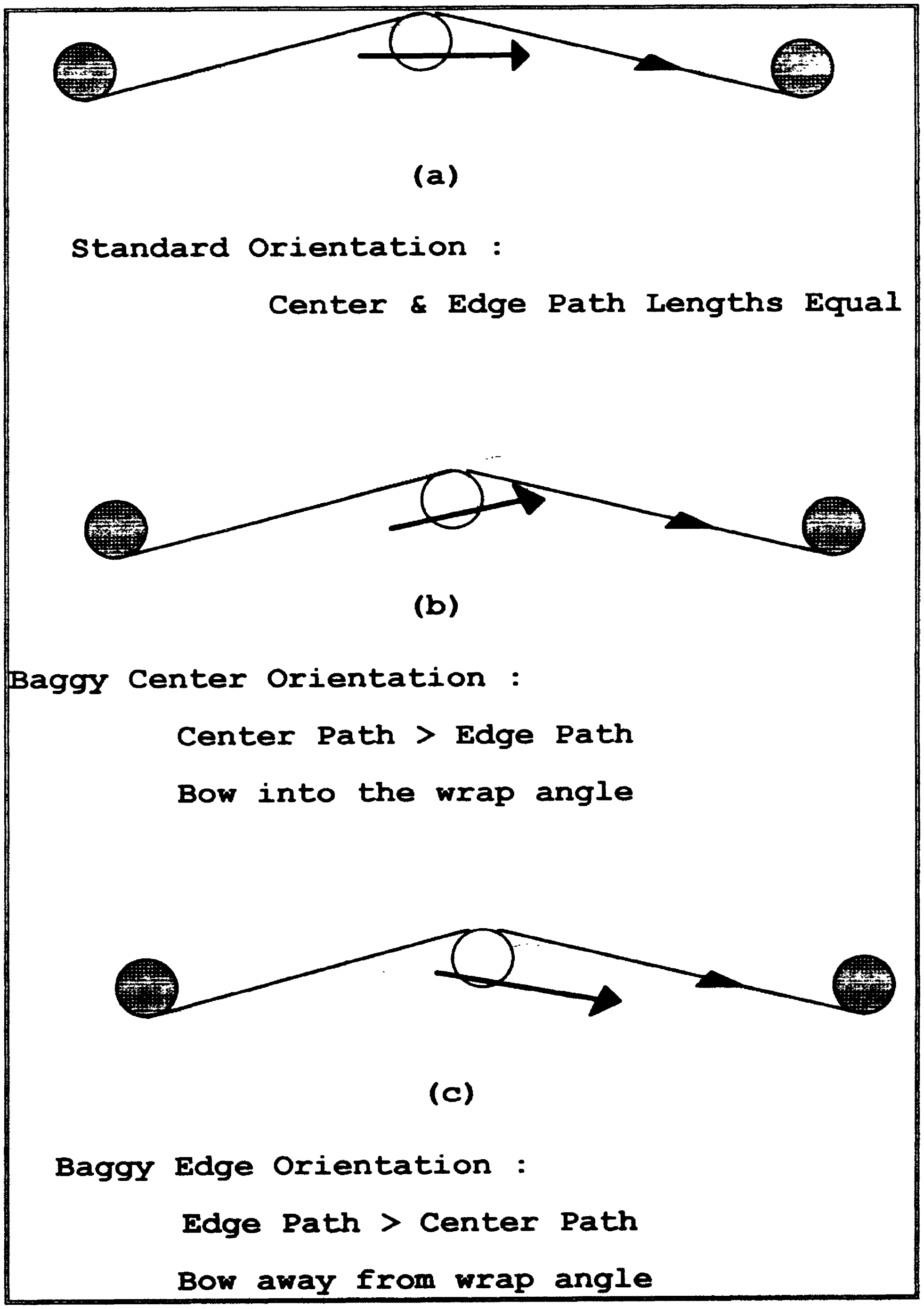

Figure 8. Spreader Roller Orientations

Errors In Measurements

Overview

The existence of error sources in experimental work is inevitable. Therefore, as Beckwith[5] said, the measurement of any property can never be considered to be "exact". It's simply a "good" measurement that must be limited to one in which the errors are too small to be significant. This significance depends primarily on the use to be made of the measured quantity.

Classifications

In general errors could be classified into three different types:

Observation Errors. Made by the observer. For example reading the wrong number on a scale, improper lighting, or vibrations.

Translation Errors. Occur when an instrument doesn't translate with complete fidelity. It includes instrument inertia and hysteresis effects. This type of error will almost always exist in some degree and must accounted for by calibrating the measuring instruments.

Signal Transmission Errors. Such as a drop in voltage along the wires between the sensor and the tachometer. This could also be accounted for by calibration or by monitoring the signal at some point along its transmission path.

CHAPTER III

CALIBRATION OF THE SENSORS

Introduction

A measurement is no better than its measuring device which indeed is no better than its calibration. The calibration of the sensors is a major factor in deciding how accurately the absolute position of the web could be detected. The process itself is simple and straightforward. For each micrometer displacement position a sensor output reading, in volts, is measured. This reading, in actuality, represents the area of the sensor's photodiodic ray interfered with by the displaced web as illustrated in figure 10. A set of micrometer displacements versus output voltages were recorded and analyzed in search of appropriate calibration curves.

Equipment

The calibration set up included the following equipment items :

- Two FIFE SE-11-IT sensors
- One 0.0001" resolution micrometer
- Two hp power supplies
- Two multimeters
- Two 500 Ohm resistors
- 17.25" wide polyethylene web (Material)

Calibration Setup

The calibration setup is shown in figure 9. It consists of one FIFE sensor and one high precision micrometer both mounted into a support plate via two specially designed brackets. A strip of web, 1" x 0.5", is glued to a plastic holder that fits tightly onto the micrometer. The web is moved by turning the advance knob of the micrometer.

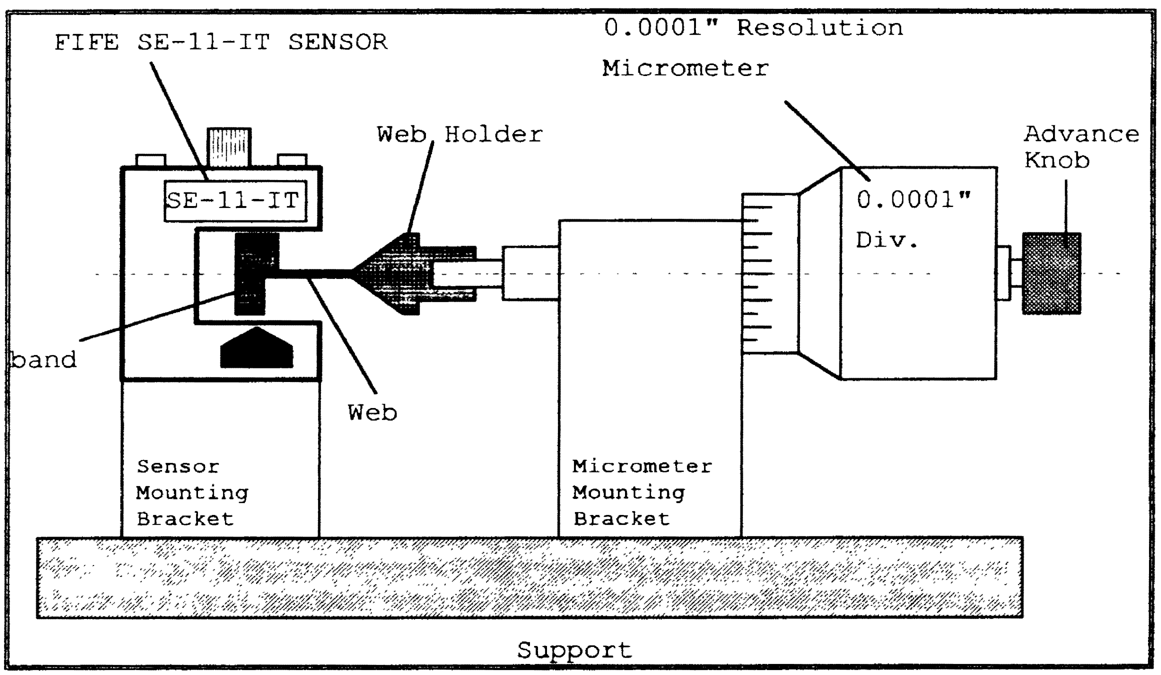

Figure 9. Calibration Setup

Factors Affecting Calibration

Web Effects

There are many important factors involved in the calibration process. Those that depend upon the web's physical properties are discussed next; others are discussed in following sections.

First, since each sensor has to be separately calibrated, it's required to maintain the same experimental conditions for all sensors. These conditions include the setup alignment, micrometer range, and especially the position of the web strip with respect to the sensor's photodiodic ray as shown in figure 10.

The second factor is the sagging behavior of the web as it is displaced across the interferometer. This behavior is shown in figure 11. The web's beam stiffness is low; as a result the web tends to sag due to its own weight. This was also unavoidable under the experimental setup used. The way the strip of web tends to bend downward, under its own weight, as shown below in figure 11, is a significant factor especially if a long strip of web is being used. However, this could be avoided by means of putting the web under some sort of tension. The way I minimized this effect is by using a short strip of web long enough to cover the band range.

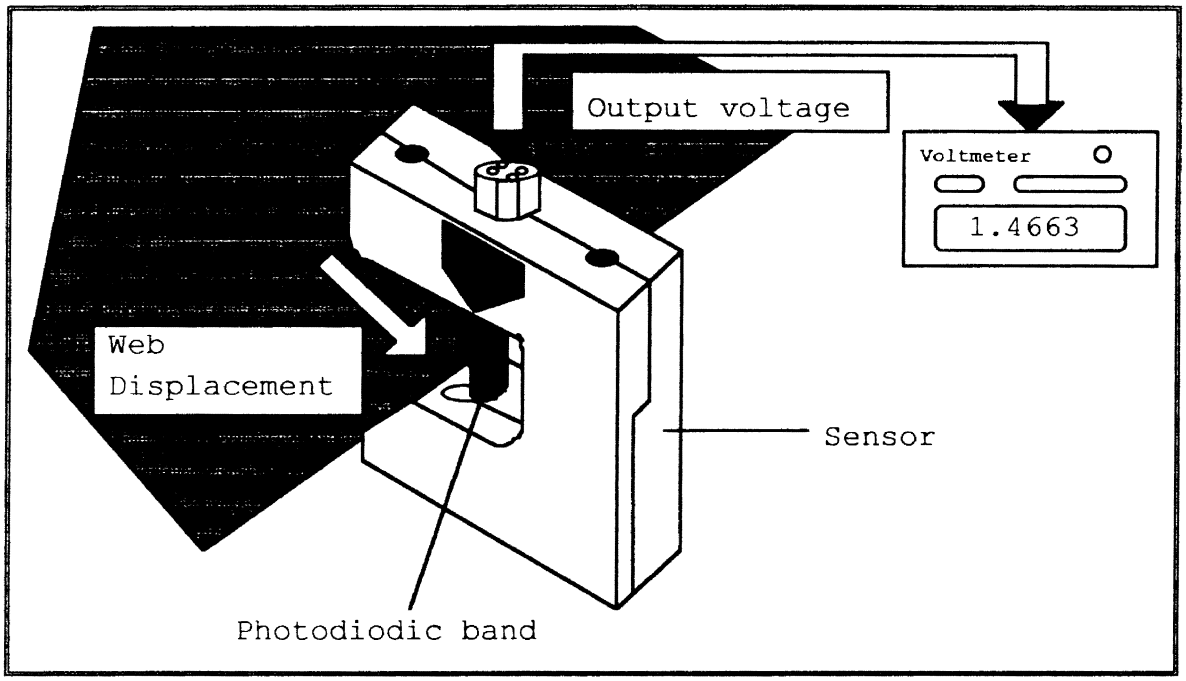

Figure 10. Displacement To Voltage

The third factor deals with making sure that the web plane is perpendicular to the plane of the sensor's band. Figure 12(a) shows what this should look like. Figures 12(b) and (c) show two possible bad positions. Table 1 has sample data for all three cases shown in figure 12 and Figure 13 has the corresponding plots.

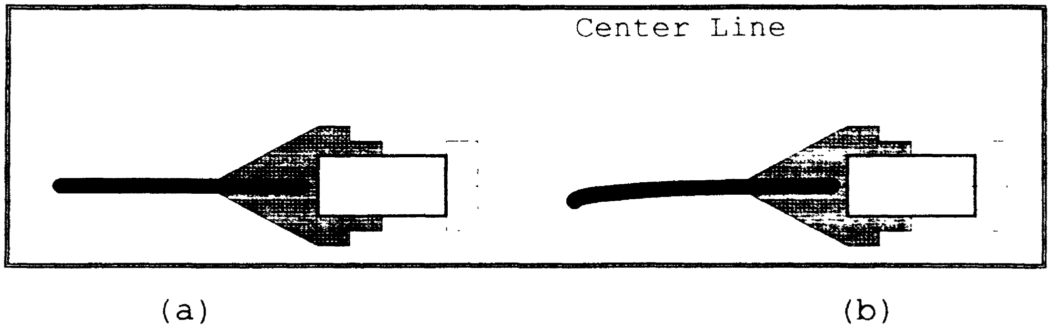

Figure 11. Sagging Behavior Of Web Strip
(a) Ideal Case
(b) Real Case (Sagging)

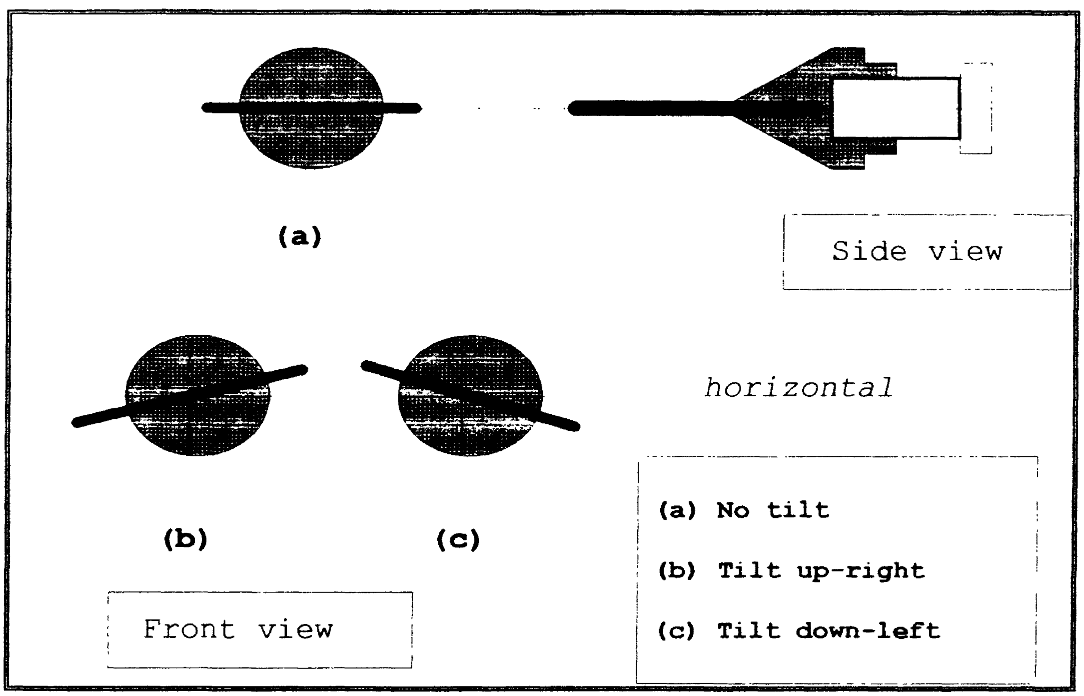

Figure 12. Tilt Effects

The final major factor in the calibration process was the number of data points taken in each test. This was a direct consequence of the way the setup was made (see figure 9). First, half resolution increments (0.0125 inches) were tried but resulted in non smooth increasing data. As previously mentioned the intensity of the output readings is proportional to the opaqueness of the material interfering with the sensor's detection band. The darker (the less transparent) the material is the more intense the output voltage is. Therefore, if a material is irregular, having one side less reflective than the other even to an extent where the human eye can't detect it, Fife's SE-11-IT sensors can detect the difference and show different but similar behavior for each side. This effect is shown below in figure 14.

Because of the above reasons the number of data points in each test was limited to nine equally dispersed over a range of 0.20 inches, which is the total width of the photodiodic ray. Each two consecutive points are a full micrometer revolution apart equivalent to 0.025 inches.

TABLE 1

DATA SHOWING TILT EFFECTS

No Tilt		up - r tilt		down - l tilt	
pos.	**volts**	**pos.**	**volts**	**pos.**	**volts**
0.000	0.516	0.000	0.581	0.000	0.679
0.025	1.002	0.022	1.054	0.028	1.176
0.050	1.535	0.047	1.583	0.053	1.727
0.075	2.095	0.072	2.131	0.078	2.282
0.100	2.623	0.097	2.626	0.103	2.778
0.125	3.069	0.122	3.044	0.128	3.201
0.150	3.481	0.147	3.441	0.153	3.602
0.175	3.865	0.175	3.813	0.175	3.990

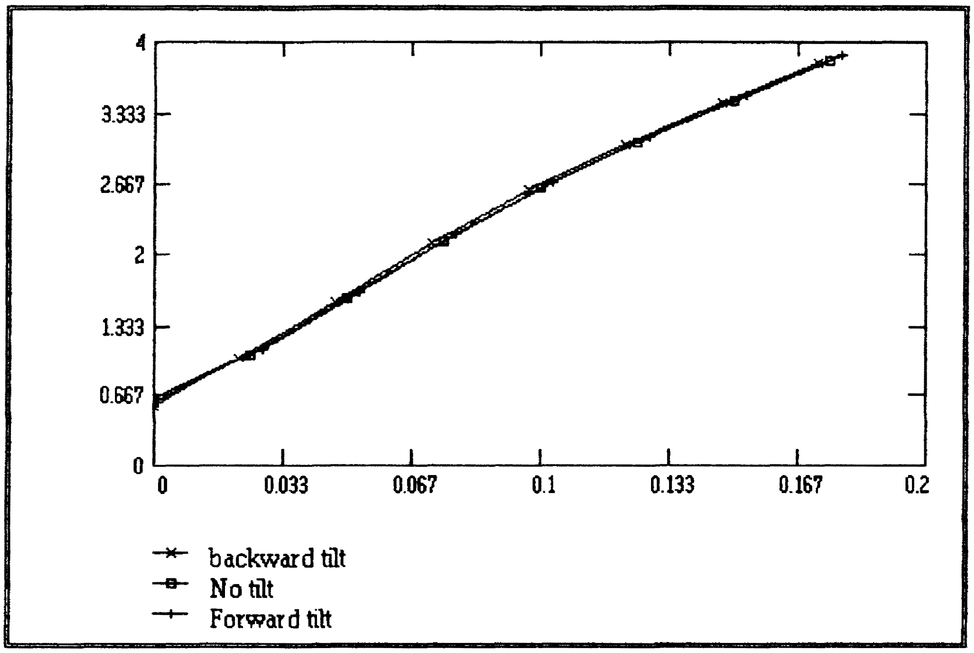

Figure 13. Tilt Effects (Graph)

<u>Hysteresis effects</u>

The calibration setup shown in figure 9 allows web advancement in two opposite directions. First, the "forward" type motion as shown in figure 15. In this case, the micrometer readings will start from a starting point, assumed to be the zero position point, and gradually increase to an end point after 0.20 inches of absolute micrometer displacement. Between these endpoints several evenly space points were recorded. Second, a "backward" type motion is considered as shown in figure 16. In this case the motion is reversed and the previous ending point becomes the new starting point. The same intermediate points were recorded again and analyzed in a similar way to the first case data. Data for both types of motion are recorded in table 2.

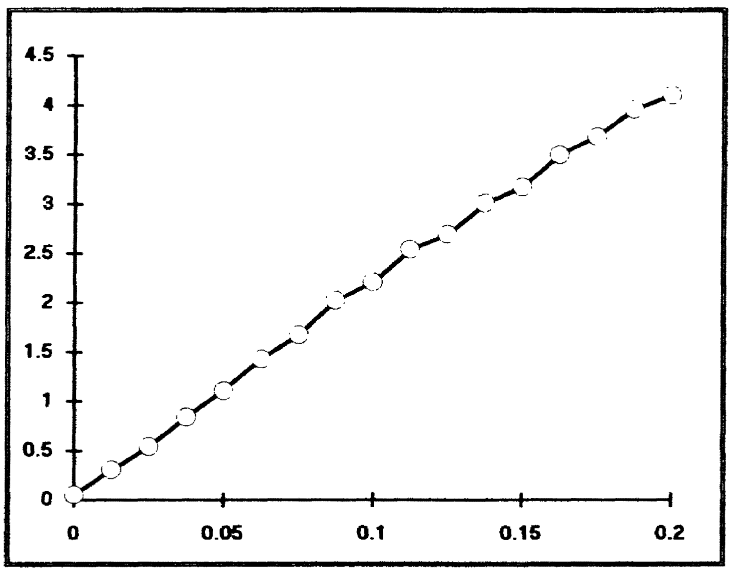

Figure 14. Plot Showing The Reflectiveness effects

TABLE 2

DATA ILLUSTRATING HYSTERESIS EFFECTS OF THE MICROMETER TEST 2, 4, AND 6 ARE BACKWARD ADVANCE TEST 1, 3, AND 5 ARE FORWARD ADVANCE

Microm.	**Output**					
(inch.)	**test1**	**test2**	**test3**	**test4**	**test5**	**test6**
0.000	0.692	0.683	0.685	0.682	0.688	0.683
0.025	1.180	1.171	1.174	1.169	1.175	1.169
0.050	1.714	1.705	1.707	1.704	1.708	1.704
0.075	2.245	2.238	2.240	2.236	2.241	2.236
0.100	2.716	2.710	2.712	2.709	2.712	2.709
0.125	3.115	3.111	3.113	3.111	3.112	3.110
0.150	3.505	3.503	3.503	3.501	3.502	3.500
0.175	3.884	3.882	3.882	3.880	3.881	3.880
0.200	4.253	4.252	4.252	4.251	4.250	4.250

Analysis of the above two cases showed in clear fashion the hysteresis effects of the micrometer. Although these effects were relatively small they were big enough to be effective , which made me decide to use a forward test only since it showed better results.

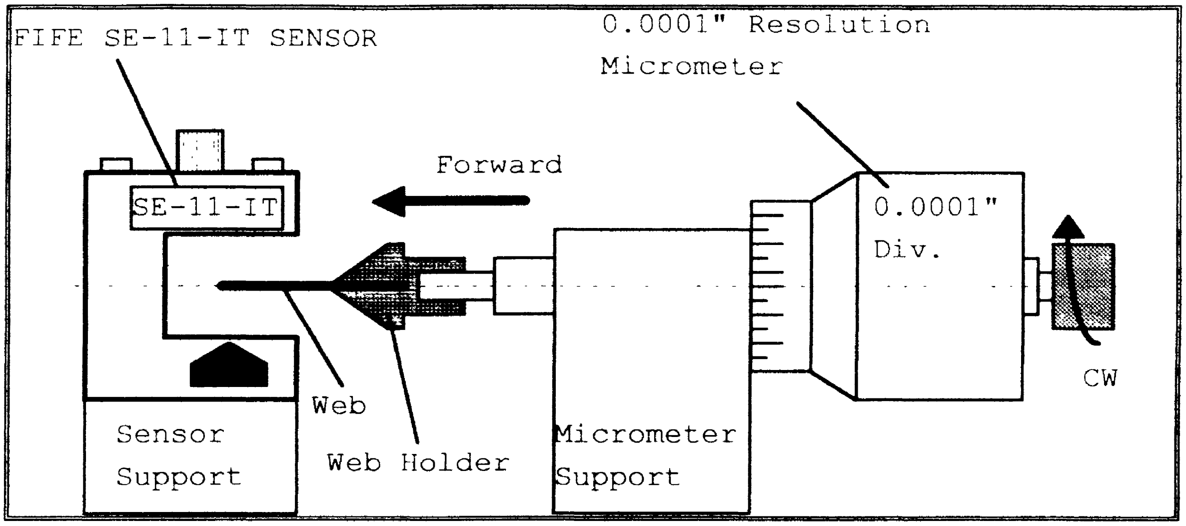

Figure 15. Forward Type Advance

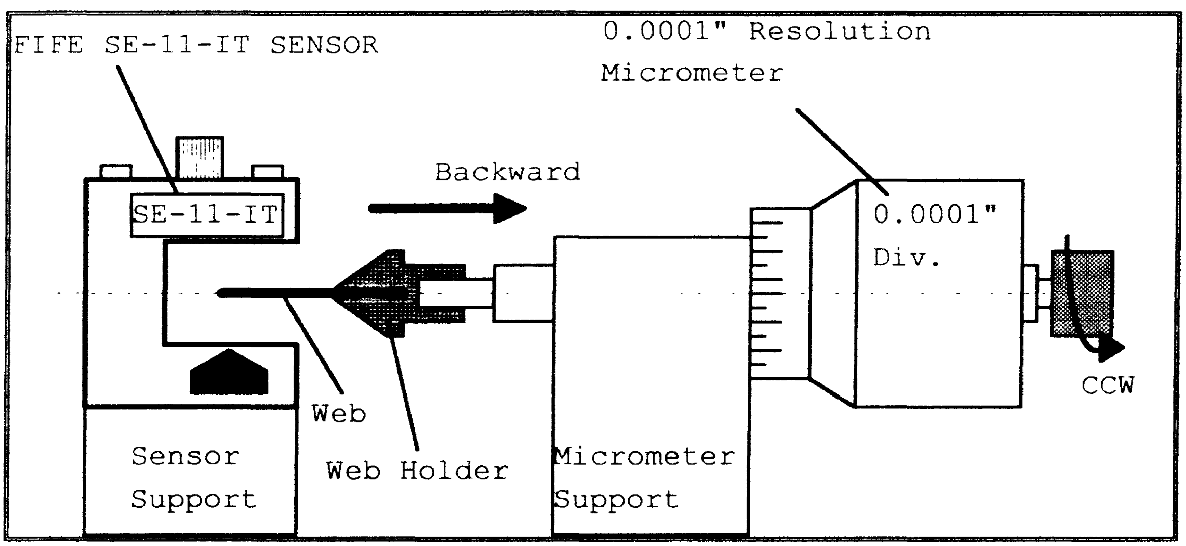

Figure 16. Backward Type Advance

Cubic Splines

Before we talk about the calibration let's talk a little bit about the different types of curve fits used in this process: linear, cubic, and cubic spline. The linear fit is simply a linear approximation of the sampled data points. It's usually characterized by a correlation factor, between -1 and +1, which measures how dependent and how strong the relationship is between the data and it's curve fit. The closer to zero this factor is the more uncorrelated the sample data and its fit are. And by a mean square error, or a root mean square error, which also measures how close the fit remains to the actual data. When this error is zero the fit matches the sampled data exactly.

A cubic fit is a third order polynomial approximation of the given data. This curve fit, like in the linear case, may or may not pass through any points. It's also characterized by a mean square error in the same way it is described earlier.

A spline curve, also called the minimum-energy curve, is unique for the same set of control points. It can be drawn for any set of n points that imply a smooth curve. The spline deforms elastically touching all data points. A cubic spline on an interval [a,b] is an approximation by a piece wise cubic function that agrees at successive subdivision points a=x0,x1,..,xn=b and has a continuous first and second order derivatives for a <= x <= b. Conditions must also be imposed at a and b: say we require same first derivatives at these points. Figure 17 shows all three types of fits described above.

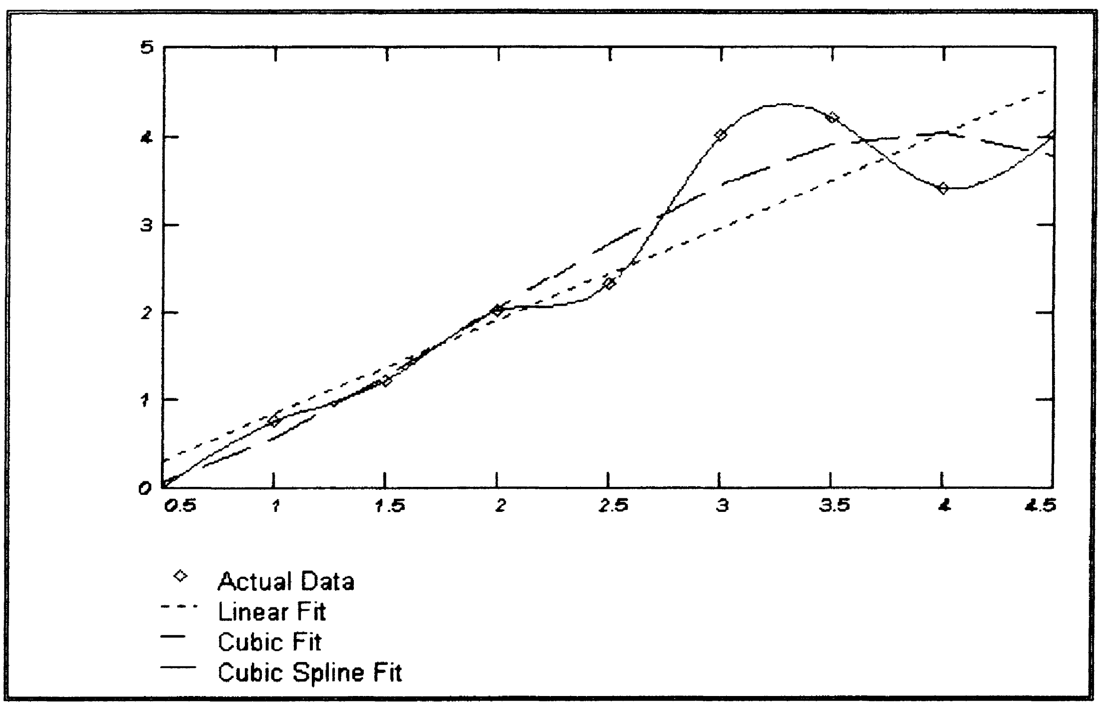

Figure 17. Linear, Cubic, And Cubic Spline Fits

Taking Calibration Measurements

Each sensor was calibrated separately. The calibration data was analyzed with linear (sensor s1), cubic (sensor s1), and cubic spline curve fits (sensors s1 and s2). The data was analyzed by means of fitting it to a suitable curve fit, then computing the absolute position, in inches, for a given output voltage. The calculated absolute position is then compared to the measured value for the same voltage. An error for the absolute position at that point is thereafter computed and compared to the desired error which is in the order of a ten thousand of an inch.

Both linear and cubic fits do not necessarily pass through all calibration points. Therefore, approximated absolute position at a certain voltage can be easily computed from the fit equations. If the curve fit passes through a given point, the measured and computed absolute positions at that point would be identical, hence the error would be zero.

For the cubic spline, which passes through all calibration points, the absolute position at a certain voltage is computed in the following way: First, all the data points, except the point at which the absolute position is to be calculated, are used to generate the desired curve fit (see figure 18). Second, Interpolation is used to find the position at the eliminated point. This process is repeated for all data points except for the endpoints. This procedure was also done with three eliminated points (see figure 19).

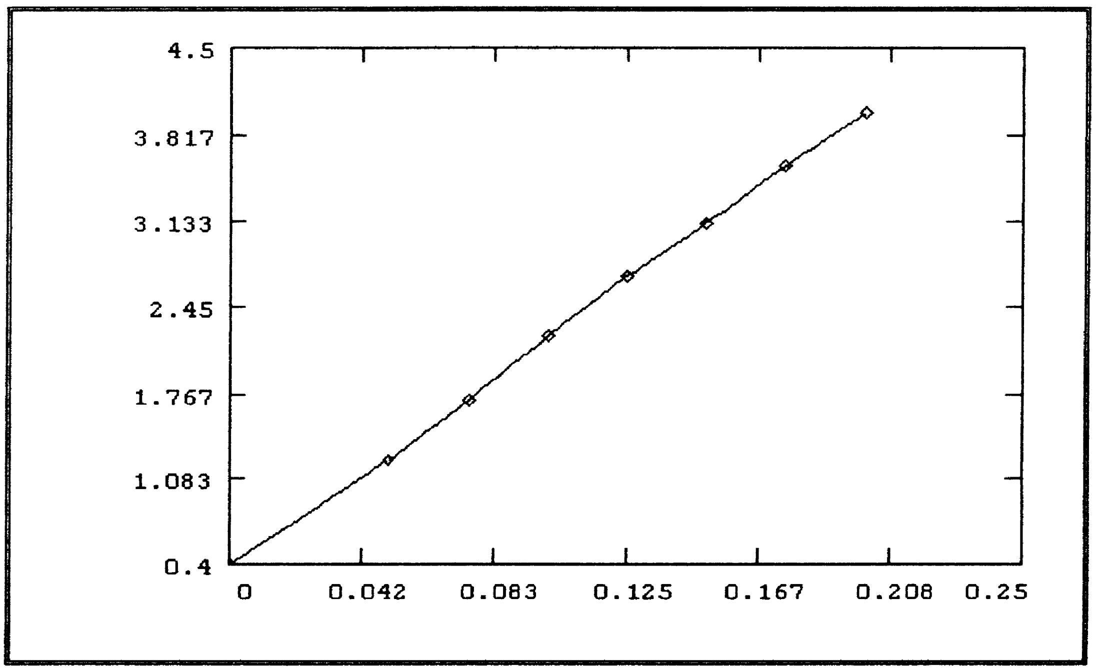

Figure 18. One-Point Elimination

By increasing the number of eliminated points from one to three and interpolating at the center point the interpolation interval is doubled as shown in figures 18 and 19. ***Comparing error changes due to this effect***

lead to the conclusion that if the error changes by an order of magnitude, say from few ten thousands to few thousands of an inch, as the interpolation interval is doubled, going from less one point to less three, we can safely and strongly assume that if the gap is halved, i.e. no points eliminated, the error will drop by an order of magnitude, say from few ten thousands to few hundreds of thousands of an inch.

On the basis of this assumption relies the validity of this calibration. Experimental results strongly backup this validity.

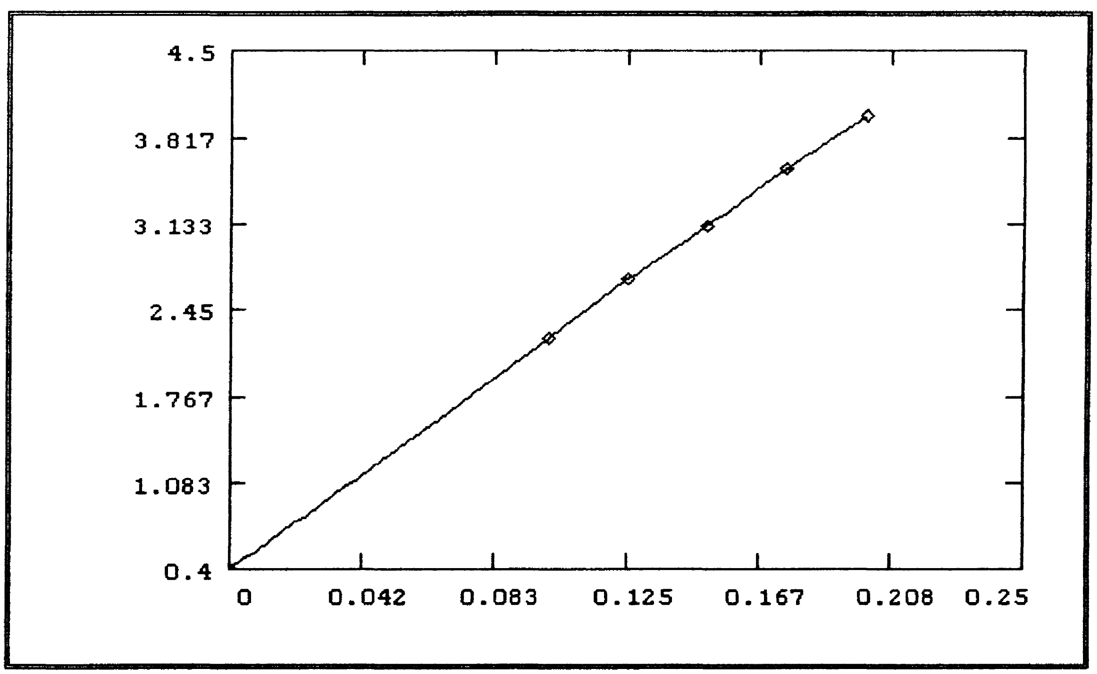

Figure 19. Three-Point Elimination

A curve fit is "acceptable" if and only if the worst error generated between a measured and calculated absolute positions is less than a desired accuracy threshold (in this case one ten thousands of an inch). Although the sensors were thought to have linear behavior, experimental results showed otherwise. The following section describes in details the calibration results.

Calibration

The calibration data contains micrometer position readings ranging from 0.000 to 0.200 inches versus sensor output voltages going from 0.400 volts to about 4.000 volts, which corresponds to the manufacturer's linearly smooth region of the sensor. The sensors were actually calibrated and tested by the manufacturer. The linearity plot for a typical SE-11 sensor used with a 100% opaque web is shown in figure 20.

One full revolution increments of the micrometer were used. Limiting the number of calibration points to nine equally spaced and 0.025 inches apart. Although this was thought to be a disadvantage originally, it did not, as will see in upcoming sections, affect or reduce the calibration accuracy.

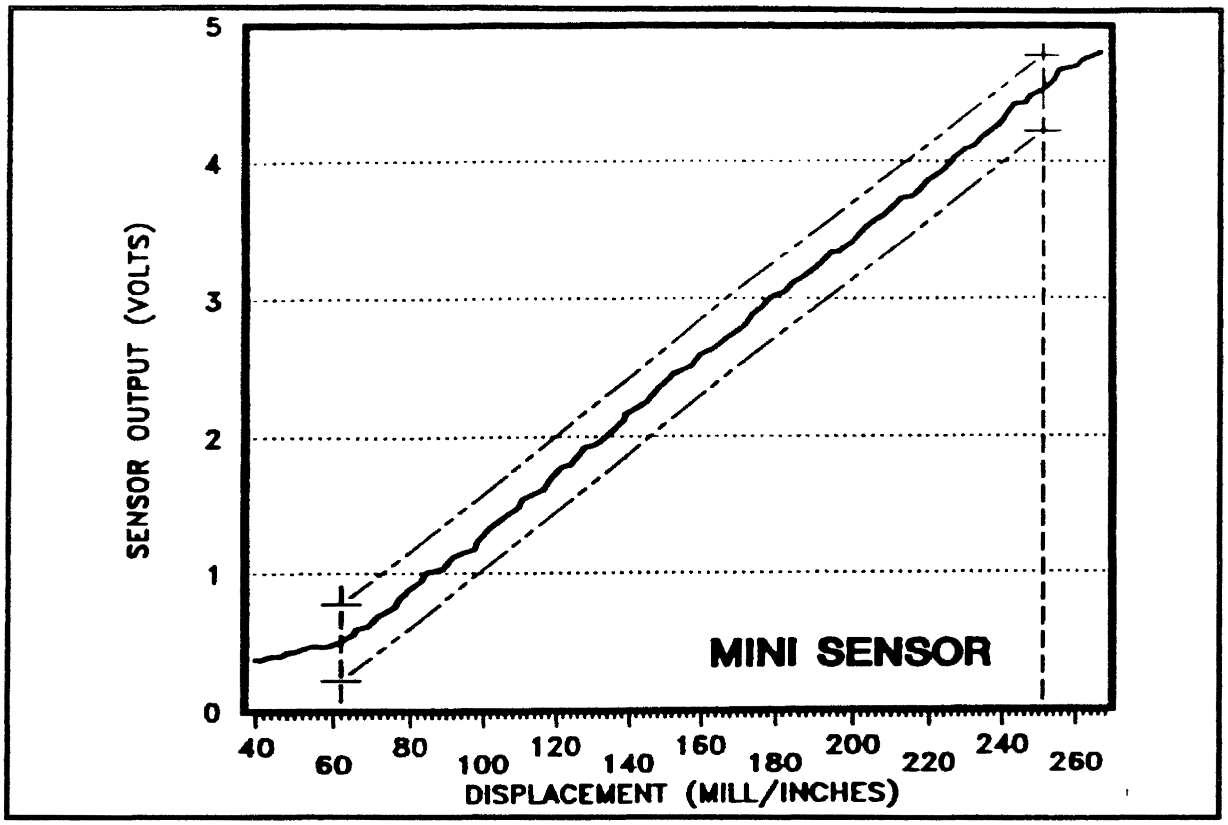

Figure 20. Linearity Plot

Sensor s1 Calibration

The following table (table 3) contains the final data used in the calibration of sensor s1. The table contains micrometer displacements in inches versus corresponding sensor readings in volts. Voltage is analyzed with respect to micrometer displacement. For sensor s1, all linear, cubic, and cubic spline studies are presented in this work. However, for sensor s2 linear and cubic analyses are eliminated.

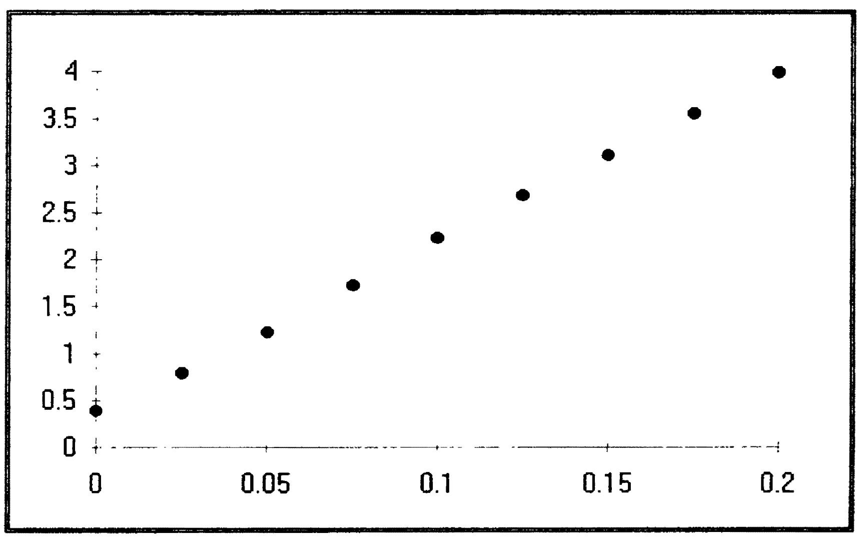

Figure 21. Sensor s1 Calibration Data

Linear Fit. When the data of table 3 was approximated by a linear curve-fit it resulted in the curve shown in figure 21. The linear curve was given by equation (2.1):

$$linear\_s1(x) = 18.239*x + 0.368 \qquad (2.1)$$

The correlation factor is 99.9685% and the mean square error is 0.001124 which is too high especially if we're measuring displacements as little as 1 or 2 thousands of an inch.

TABLE 3

CALIBRATION DATA FOR SENSOR s1

Micrometer	**Average Output Voltage**
(inches)	**(volts)**
0.000	0.4001
0.025	0.8016
0.050	1.2352
0.075	1.7129
0.100	2.2199
0.125	2.6875
0.150	3.1169
0.175	3.5592
0.200	3.9800

Table 4 shows measured versus computed absolute displacements of the web and their relative error for a set of known voltages. The error values which were as high as 0.0029 inches are more than ten times higher than our error criteria of 0.0001. Therefore, a linear fit could not be used.

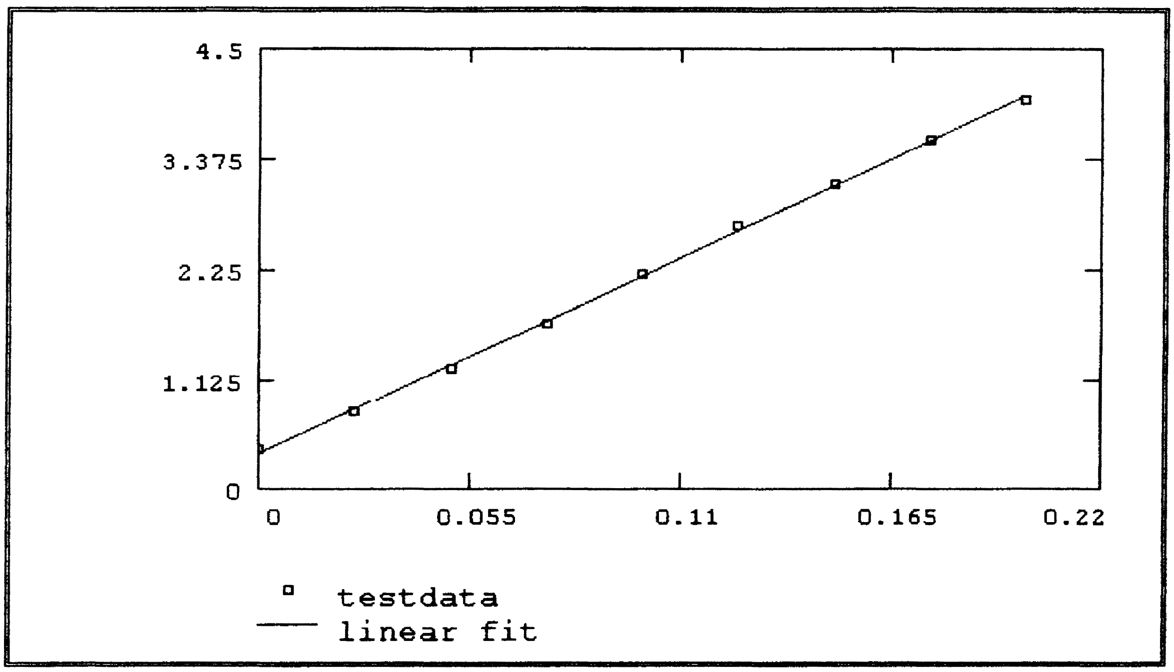

Figure 22. Linear Curve Fit For Sensor s1

<u>Cubic Fit.</u> Cubic fit analysis showed better results than the linear fit ones. The curve fit has a mean

square error of 0.0002 and is shown in figure 23 and is given by equation (2.2):

$$cubic\_s1(x) = -130.27 * x^3 + 37.603 * x^2 + 15.568 * x + 0.394 \qquad (2.2)$$

TABLE 4

POSITION ANALYSIS USING LINEAR FIT FOR SENSOR s1

Voltage	**Position**		
(Volts)	**Measured**	**Computed**	**Error**
0.8016	0.025	0.0234	0.0016
1.2352	0.050	0.0471	0.0029
1.7129	0.075	0.0736	0.0014
2.2199	0.100	0.1017	0.0017
2.6875	0.125	0.1275	0.0025
3.1169	0.150	0.1509	0.0009
3.5592	0.175	0.1757	0.0007

Table 5 shows absolute position analysis using a cubic fit. Error values are smaller than linear fit results however still as high as 0.0012 inches which is still much too high to tolerate.

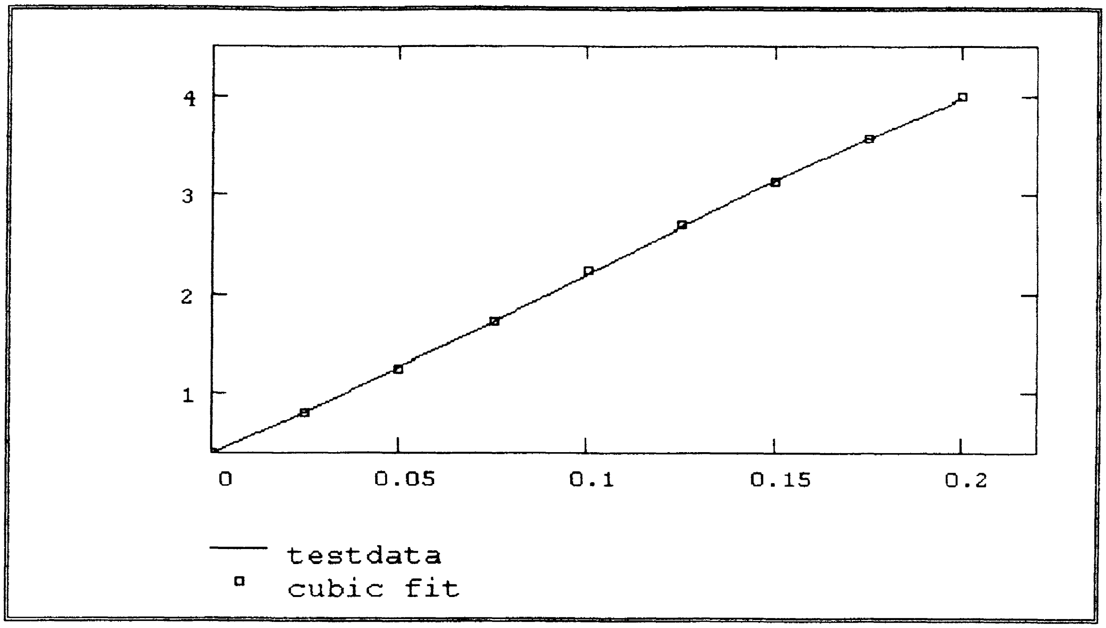

Figure 23. Cubic Fit For Sensor s1

TABLE 5

POSITION ANALYSIS USING CUBIC FIT FOR SENSOR s1

Voltage (Volts)	**Position**		
	Measured	**Computed**	**Error**
0.8016	0.025	0.0248	0.0002
1.2352	0.050	0.0492	0.0008
1.7129	0.075	0.0747	0.0003
2.2199	0.100	0.1012	0.0012
2.6875	0.125	0.1258	0.0008
3.1169	0.150	0.1489	0.0011
3.5592	0.175	0.1748	0.0002

Cubic Spline Fit. A cubic spline fit was finally called upon. The advantage of a spline fit is that the curve will pass through all calibration points which will give accurate displacement interpolations especially close to the spline points. For sensor s1 the spline fit is shown in figure 24. For the cubic spline it was necessary to see ***how the error changes with respect to the size of the interpolation interval.*** To get a feel of this, absolute position values were computed for different size gaps. First, by eliminating one point hence interpolating at that particular point. Then, by eliminating three points making possible to interpolate at the center of the interval: a point with known absolute position.

The absolute position analysis results are shown in table 6 (one point elimination) and table 7 (three point elimination). Error values are in the ten thousands of an inch range for the one point elimination case (max = 0.0006). However, as the interval is doubled error values jumped to the thousands of an inch (max = 0.0033). Thus, error was multiplied by a factor of 5 as the gap is doubled. As we mentioned earlier, we hope that if the gap is halved the error will shrink by a factor of 5 thus making it about 0.0001 or less.

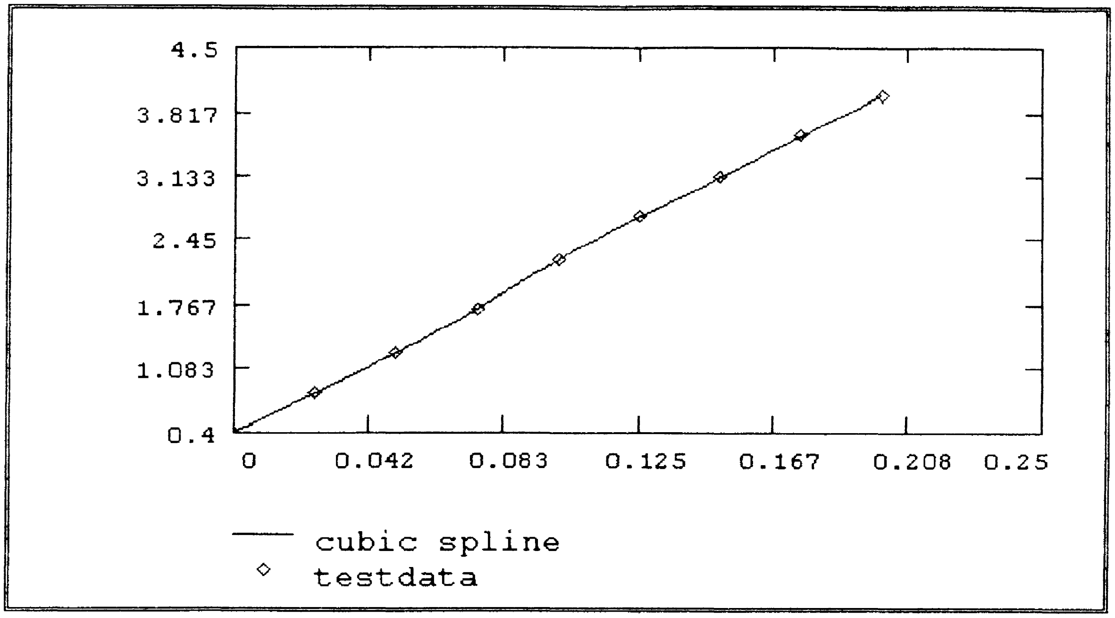

Figure 24. Cubic Spline Fit For Sensor s1

TABLE 6

POSITION ANALYSIS USING CUBIC SPLINE FIT
FOR SENSOR s1 (ONE POINT ELIMINATION)

Voltage (Volts)	**Position**		
	Measured	**Computed**	**Error**
0.8016	0.025	0.0248	0.0002
1.2352	0.050	0.0500	0.0000
1.7129	0.075	0.0746	0.0004
2.2199	0.100	0.1004	0.0004
2.6875	0.125	0.1255	0.0005
3.1169	0.150	0.1494	0.0006
3.5592	0.175	0.1756	0.0006

TABLE 7

POSITION ANALYSIS USING CUBIC SPLINE FIT
FOR SENSOR s1 (THREE POINT ELIMINATION)

Voltage (Volts)	**Position**		
	Measured	**Computed**	**Error**
1.2352	0.050	0.0467	0.0033
1.7129	0.075	0.0738	0.0012
2.2199	0.100	0.1028	0.0028
2.6875	0.125	0.1257	0.0007
3.1169	0.150	0.1484	0.0016

Sensor s2 Calibration

The following table (table 8) contains the final data used in the calibration of sensor s2. The table contains voltages versus micrometer positions. For this sensor only cubic spline analysis is done since linear and cubic curve fits showed intolerable margins of error for sensor s1.

TABLE 8

CALIBRATION DATA FOR SENSOR s2

Micrometer (inches)	**Average Output Voltage (volts)**
0.000	0.4445
0.025	0.9018
0.050	1.4119
0.075	1.9581
0.100	2.4877
0.125	2.9316
0.150	3.3300
0.175	3.7248
0.200	4.0887

Cubic Spline Fit. As was the case with sensor s1 a cubic spline fit had to be used in order to achieve desired accuracy. The spline goes through all calibration points as shown in figure 26. Absolute position analysis is shown in table 9 for one point elimination and table 10 for three point elimination.

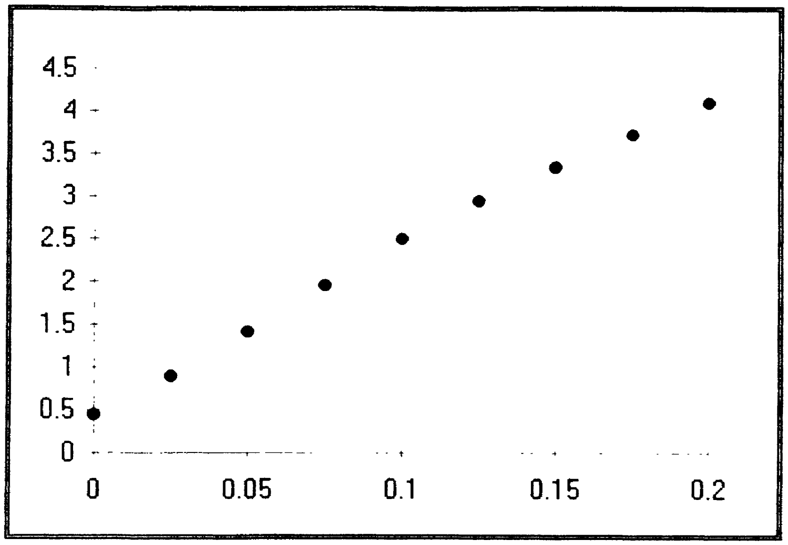

Figure 25. Sensor s2 Calibration Data

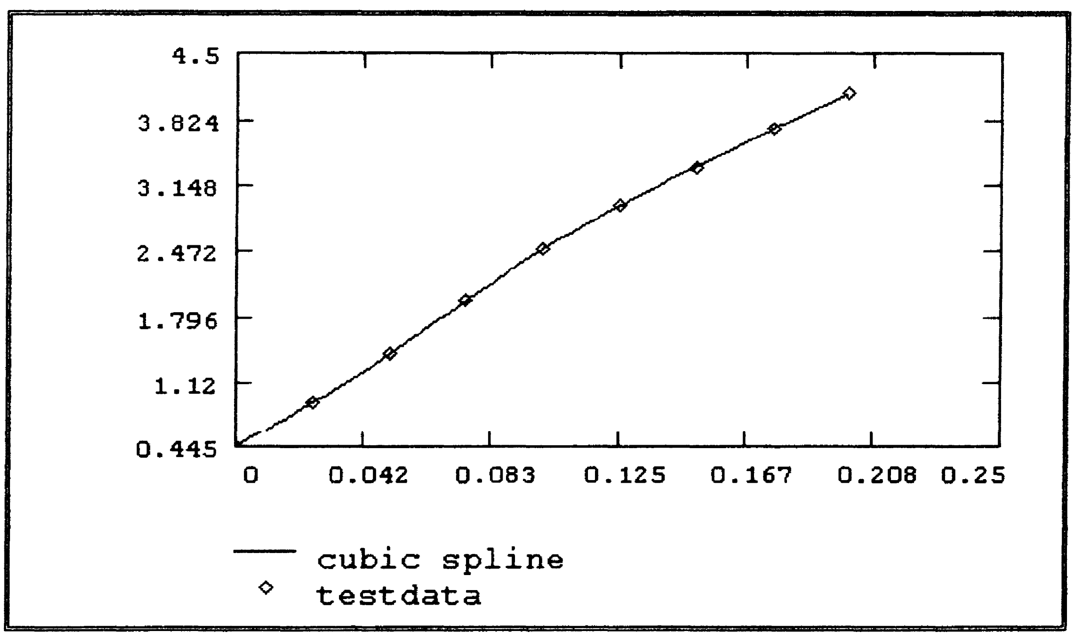

Figure 26. Cubic Spline Fit For Sensor s2

TABLE 9

POSITION ANALYSIS USING CUBIC SPLINE FIT
FOR SENSOR s2 (ONE POINT ELIMINATION)

Voltage	**Position**		
(Volts)	**Measured**	**Computed**	**Error**
0.9018	0.025	0.0245	0.0005
1.4119	0.050	0.0500	0.0000
1.9581	0.075	0.0748	0.0002
2.4877	0.100	0.1007	0.0007
2.9316	0.125	0.1250	0.0000
3.3300	0.150	0.1494	0.0006
3.7248	0.175	0.1758	0.0008

TABLE 10

POSITION ANALYSIS USING CUBIC SPLINE FIT
FOR SENSOR s2 (THREE POINT ELIMINATION)

Voltage	**Position**		
(Volts)	**Measured**	**Computed**	**Error**
1.4119	0.050	0.0458	0.0042
1.9581	0.075	0.0756	0.0006
2.4877	0.100	0.1033	0.0033
2.9316	0.125	0.1255	0.0005
3.3300	0.150	0.1478	0.0022

Standard Width Measurement

Finally, a verification test was conducted. The purpose of this test is to see if the above calibration is sound enough. The test consisted of a slice of web of constant width partially glued to a metal block as shown below (figure 27). The block/web (specimen) is then placed between the two sensors as shown in figure 28 and a width measurement is taken. The specimen is then carefully displaced along its width and another measurement is taken. The test was repeated few times after which a change in width was computed. Results of this test are shown in table 11 below.

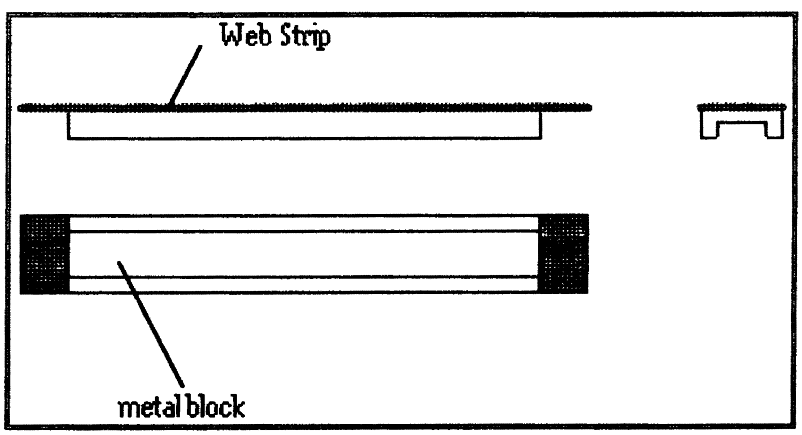

figure 27. Standard width specimen

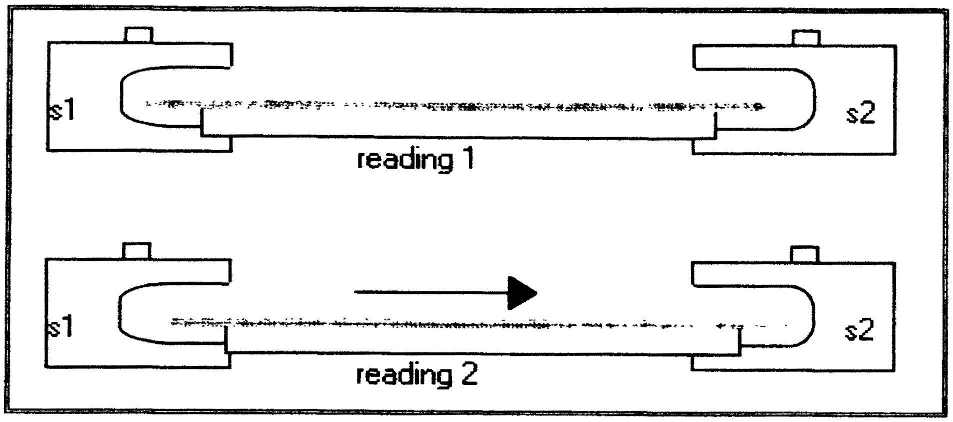

Figure 28. Standard Width Measurement

As shown in table 11, this test shows that we can repeatedly measure a fixed width up to a few ten thousandths of an inch. Therefore, the calibration of the sensors met the precision requirement. The next chapter discusses the experimental setup.

TABLE 11

STANDARD WIDTH MEASUREMENTS

Reading	s1		s2		Width
	volts	inches	volts	inches	
1	0.5142	0.0223	2.6390	0.1418	0.1641
2	1.1447	0.0512	2.1350	0.1131	0.1643
3	1.5613	0.0691	1.7820	0.0951	0.1642

CHAPTER IV

EXPERIMENTAL SETUP

Equipment

The experimental setup included the following equipment items :

- A 48" endless loop machine
- One 3" diameter cylindrical roller
- One 3" diameter spreader roller with 8000 inches radius of curvature
- One 3" diameter spreader roller with 4000 inches radius of curvature
- A 486 computer system
- An ADC16 data acquisition board
- A linear motion system
- Two FIFE SE-11-IT sensors
- Two hp power supplies
- Two multimeters
- Two 500 Ohm resistors
- 17.25" wide polyethylene web (Material)

Experimental Setup

Roller Configuration

The experiment was conducted on a 48-inch endless loop machine at the Oklahoma State University Web Handling Research center. To this machine two roller mountings were added such that to have a cylindrical roller, roller **A**, at a vertical entry span of about 34.0 inches followed by a curved axis roller, roller **B**, at a downstream location as shown in figure 29.

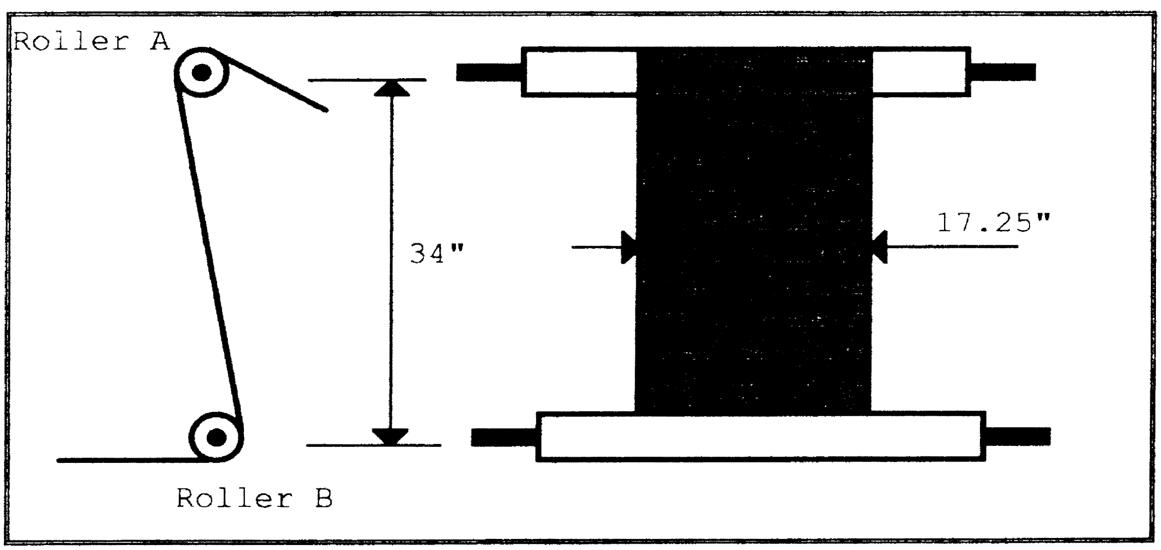

Figure 29. Roller Configuration

In figure 29, **A** is the upstream cylindrical roller. **B**, which will be the reference roller from this point on, is the downstream roller and is taken as a cylindrical roller initially to measure either no spreading, as is suggested by theoretical model, or some offset or error spreading, that results from experimental deficiencies. Then is replaced by a spreader roller. The absolute experimental spreading is then computed as the difference between the curved axis spreading and the cylindrical roller spreading.

Sensor Mounting and Adjustment

The sensors were mounted on a specially designed, fully adjustable, linear motion system. This system consisted of a 6.0" wide 30.0" long 0.75" thick metal plate, two 24.0" long rods with 0.50" diameter mounted on the plate via four end support blocks. also, a 2.50" by 3.75" carriage top mounted on two twin pillow blocks that move smoothly over the rods. This configuration is as shown in figure 30.

The sensors are mounted to the bar of figure 31 using two M-5 mounting brackets from FIFE Corporation. The bar is then attached to the carriage of figure 30 via a specially designed two-piece adjustable mounting bracket as shown in figure 31. The bracket is adjustable in the horizontal as well as the vertical direction. This will allow proper alignment of the sensors with respect to the web. Figures 32 and 33 show in more details how adjustment is done in each direction separately. Adjustment is done after slightly loosening up the four screws that hold the bracket to the carriage.

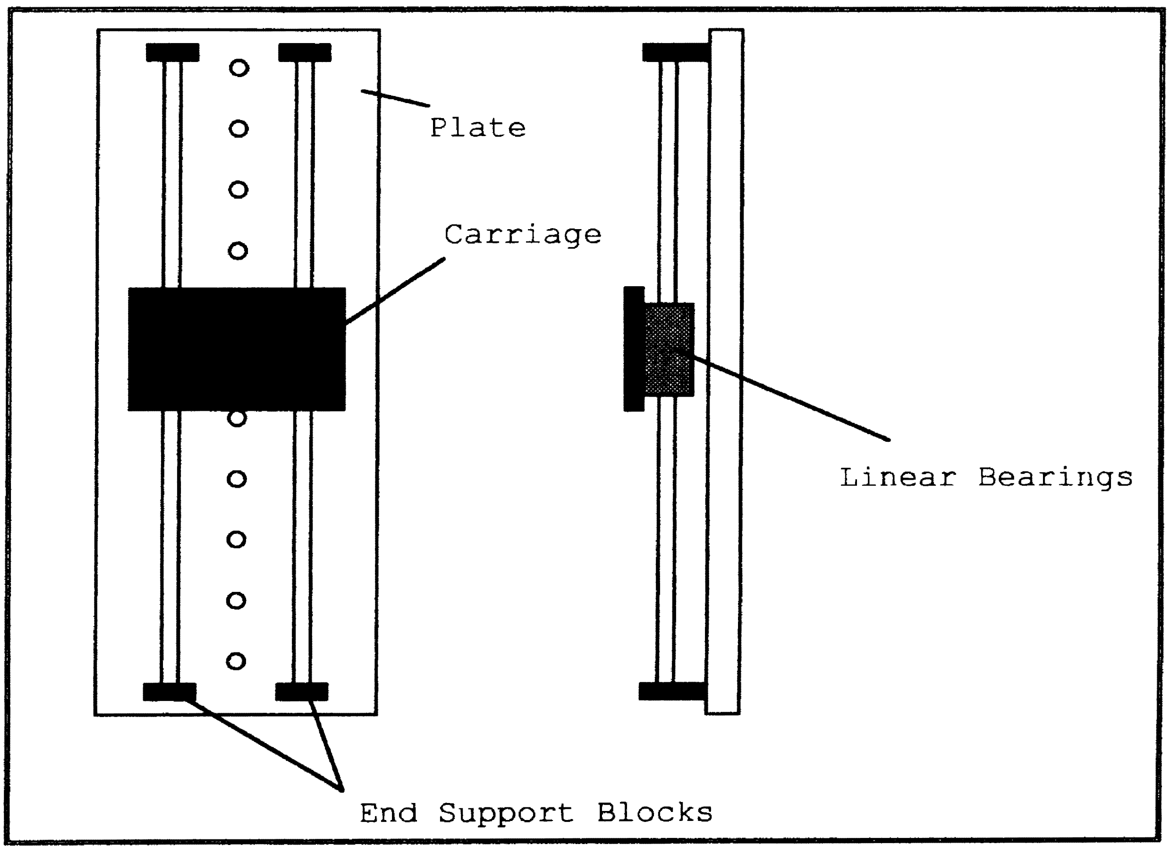

Figure 30. Linear Motion System Without Sensors

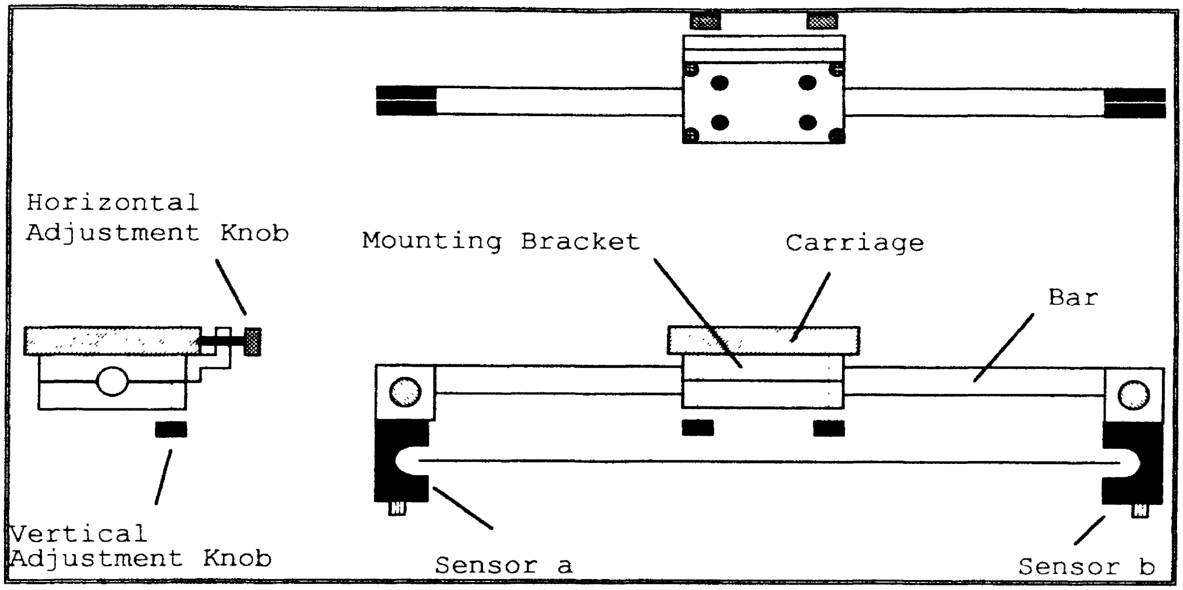

Figure 31. Sensor Mounting and Adjustment

Figure 32 shows how horizontal, or out of plane, adjustment is done. By turning the adjustment knob in the proper direction the bar carrying the sensors will rotate about its center of mass allowing the sensors to square with the web in its plane of motion. This adjustment is very important because it insures the proper positioning of the web with respect to the sensors. Adjustment is completed when the width read by the sensors is minimum as indicated by figure 32(b).

Figure 33 illustrates how vertical adjustment is obtained. If the sensors are not at the same level as shown in figure 33(a), the web width L1 will be greater than the actual width of the web being L2 as shown in figure 33(b). To rectify this, turn the adjustment knob in the right direction until minimum reading is reached. Without proper adjustment of the web and the sensors at both down and upstream measurement locations readings would be ambiguous and spreading measurements would be useless.

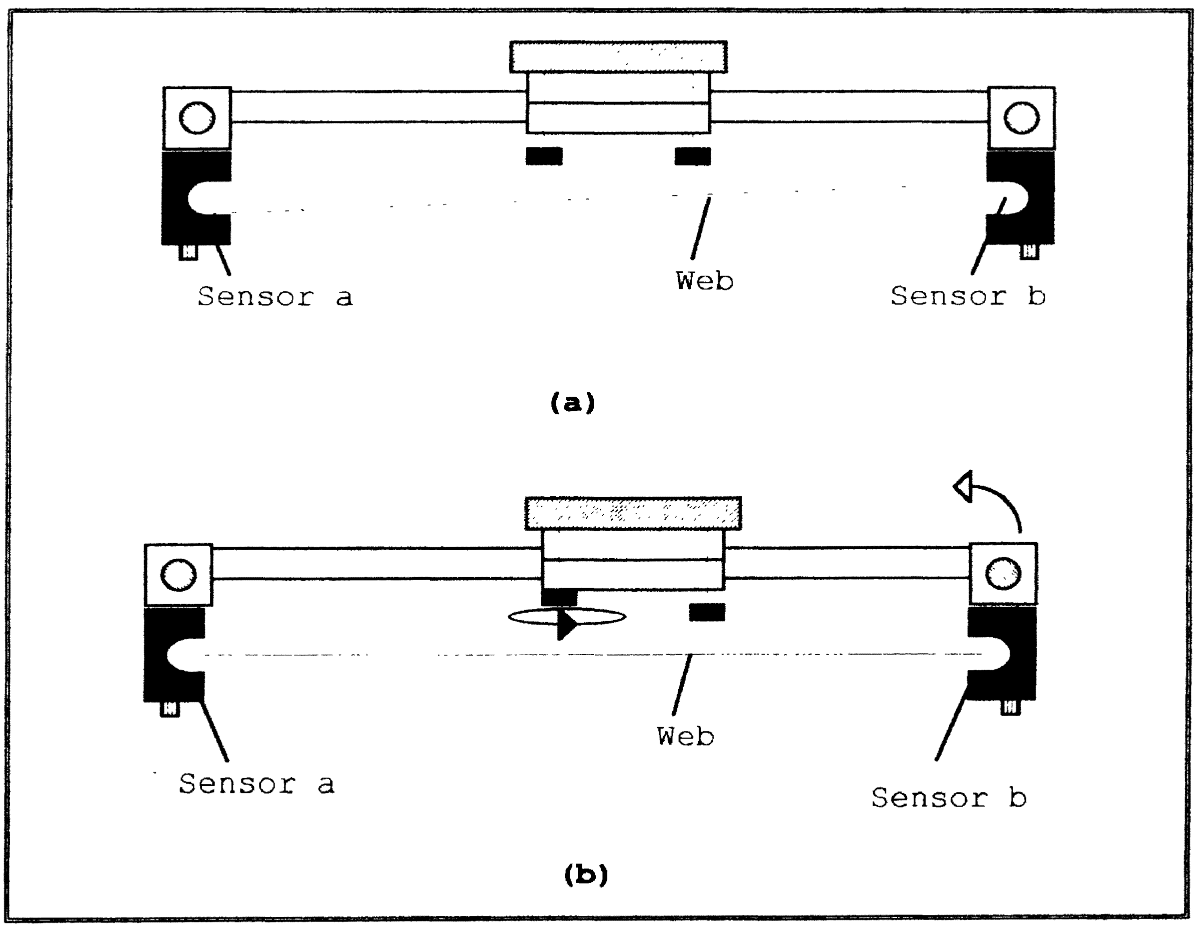

Figure 32. Sensor Horizontal Adjustment
(a) Before Adjustment
(b) After Adjustment

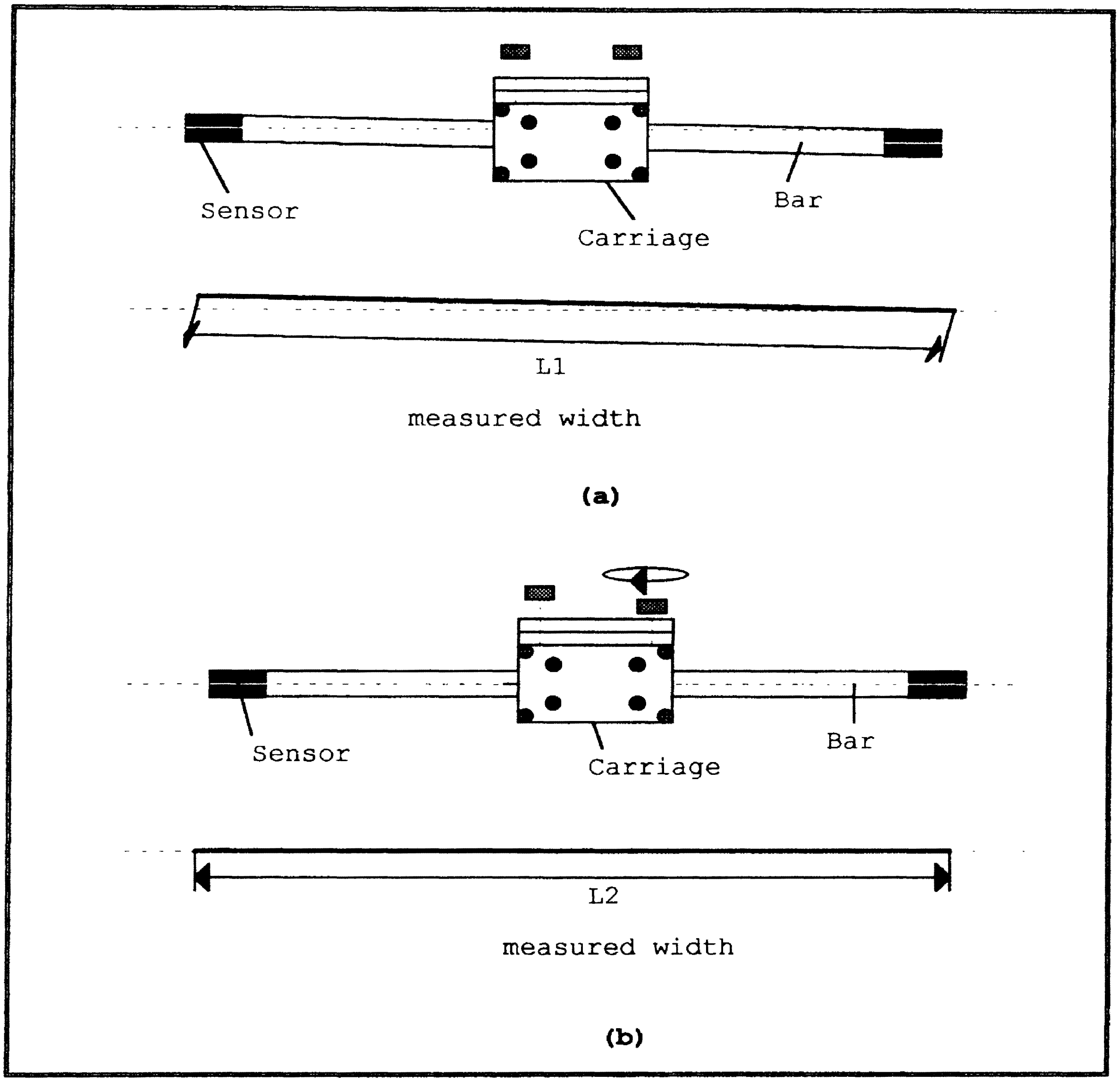

Figure 33. Sensor Vertical Adjustment
(a) Before Adjustment
(b) After Adjustment

The sensors are to be mounted on the plate as described above. The plate and the sensors are to be mounted to the frame of the machine between rollers **A** and **B** as shown in figure 34.

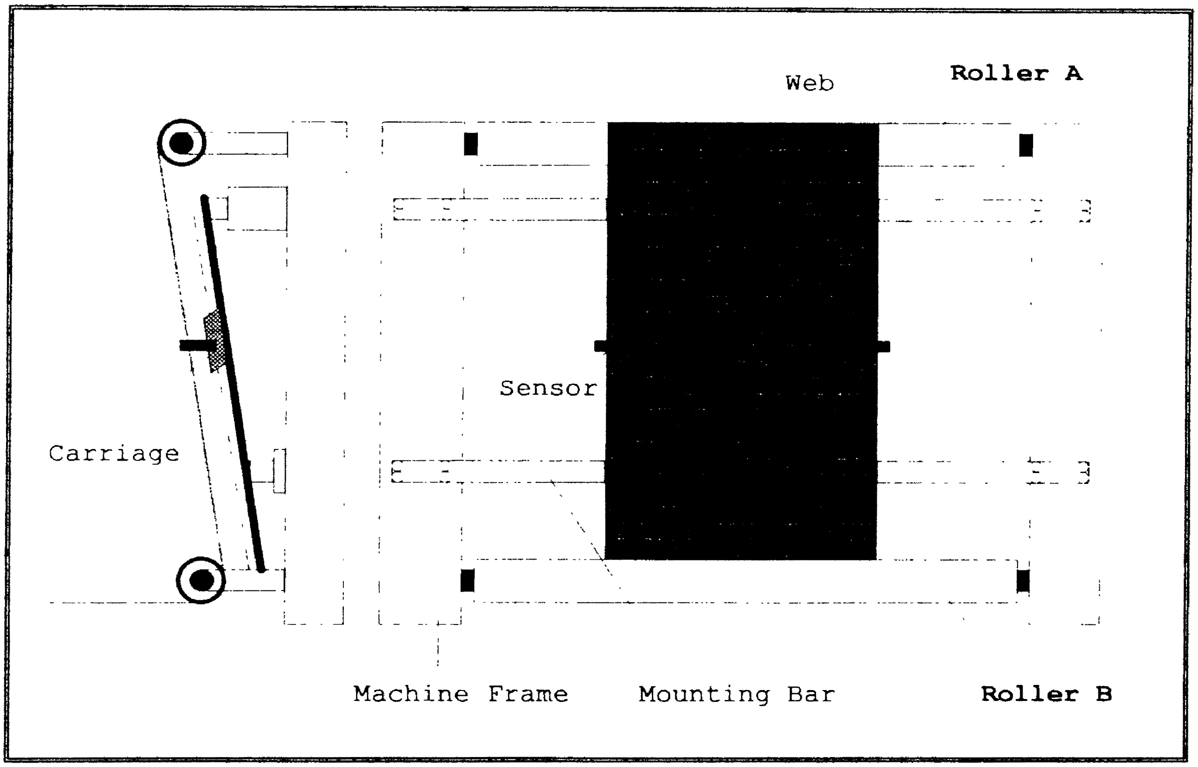

Figure 34. Plate and Sensor Mounting

The width at a given point on the web is computed at two different locations. First at an upstream location right after the upstream roller at approximately one entry span length away from the reference roller. And then at a location 2.125 inches away from the reference roller as shown if figure 34. The difference between these two measurements makes up the web spreading as it travels from **A** to **B**.

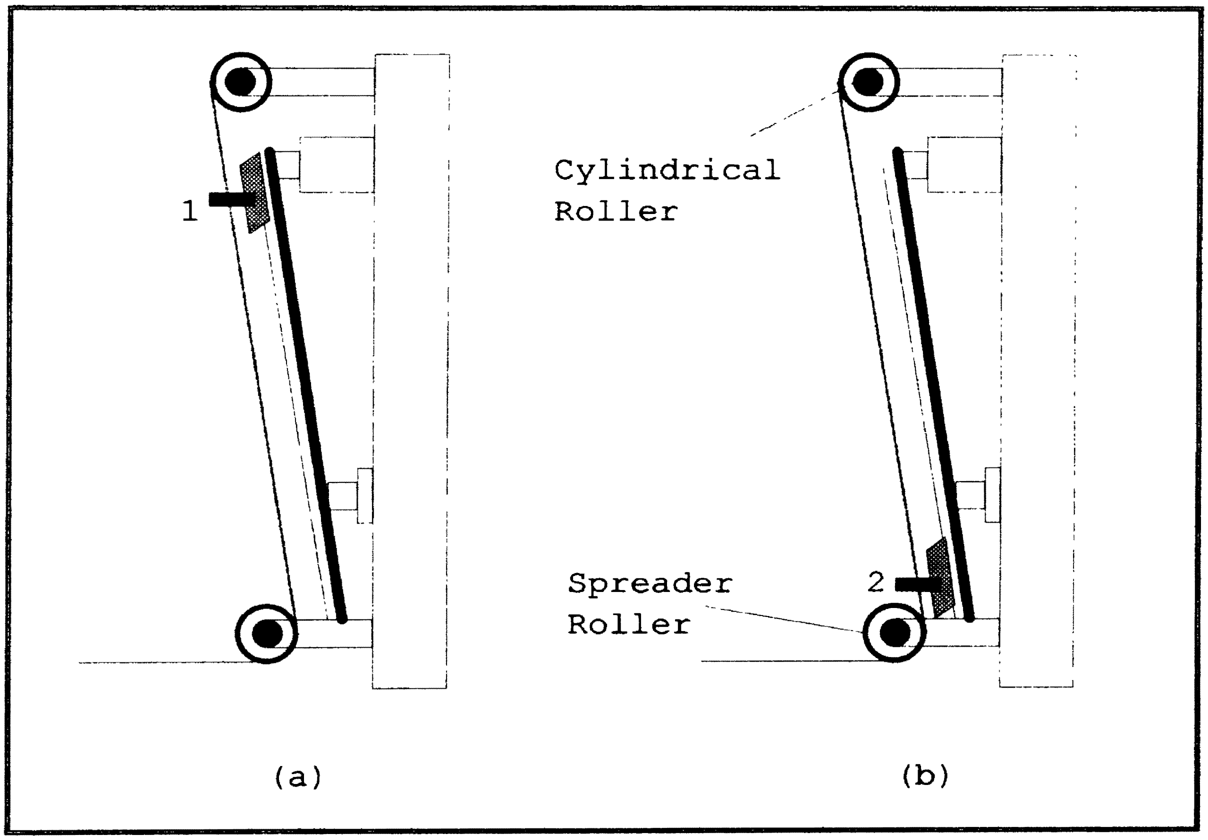

Figure 35. Measurement Locations

As previously mentioned, the web tends to curl inwards at the edges. This curling effect is related to the tension in the web and the length of the entry span. To account for this a small rod is attached to the top of the sensors as shown in figure 36. The rod flattens the web by exerting a uniform light pressure on it. The rod also serves as a partial wrinkle removal in the neighborhood of the sensors.

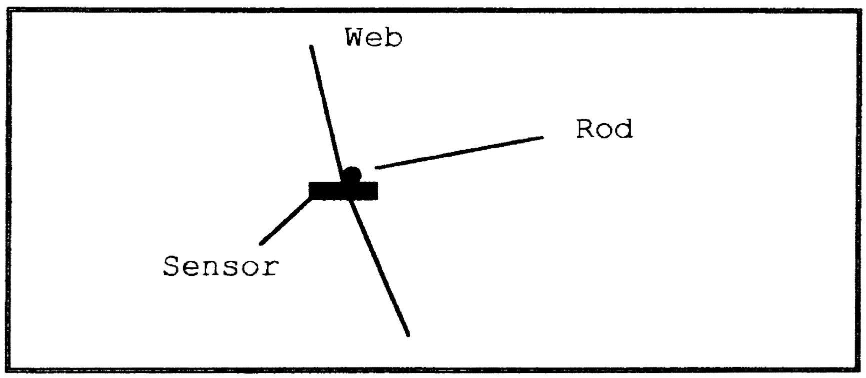

Figure 36. Rod Mounting

In order to be able to precisely locate points on the web they were marked by lines as shown in figure 37. These lines are matched to similar ones on the sensors.

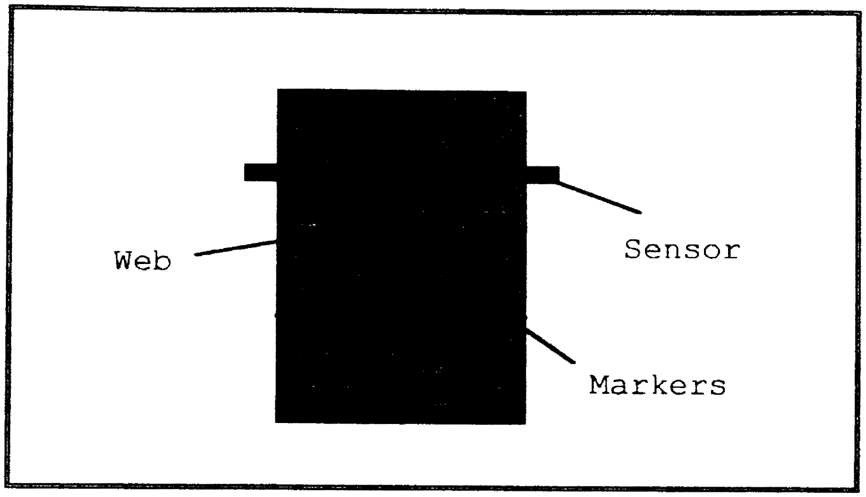

Figure 37. Markers

Data Acquisition System

Measurements are obtained by an ADC-16 analog input board. The board reads input voltages from two sensors a and b, which are connected to channels 0 and 1 of the board respectively, at an average rate of 16 conversions per sec while ensuring repeatability in noisy environment. The board is installed in a 486 IBM compatible PC and is driven by a C code that automatically transforms read voltages into displacements in inches by means of cubic spline interpolations. Figure 38 shows the sensors and their connection to the hardware.

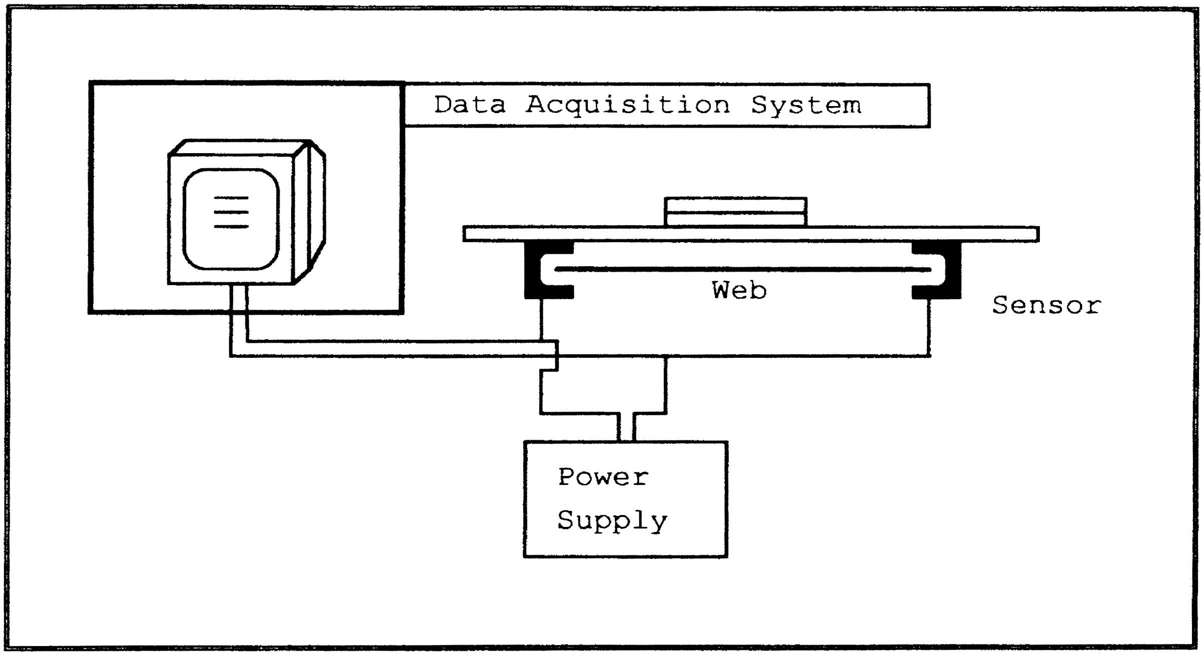

Figure 38. Hardware Connections

CHAPTER V

MEASUREMENTS AND RESULTS

Introduction

Measurements were taken using one cylindrical roller (**CR**) and two curved axis rollers with 8000 (**CAR1**) and 4000 (**CAR2**) inches radii of curvature, respectively. For each roller sets of data were taken at three different points on the web, namely **p1**, **p2**, and **p3**. At each point four different tests were conducted. In addition, for **CAR1** and **CAR2** measurements were taken at three different bow orientations with bow plane angles (BPA) equal 45, 90, and 135 degrees. These three orientations are taken such that they give maximum, intermediate, and no spreading. As a result, for the cylindrical roller twelve data tables were gathered. For each curved axis roller thirty six tables were collected making the total number exceed eighty tabulations.

The data was then analyzed and compared to theoretical model predictions.

Theoretical Model

The theoretical model is a result of the work Delahoussaye[1] did in his doctorate studies. The model was run for both spreader rollers under given experimental specifications. The model requires the following information: Web's width, thickness, poison's ratio, young's modulus, and tension; Roller base radius, wrap angle, bow plane angle, and radius of curvature. table 12 summarizes the above information.

The results of running the model are summarized in table 13. In this table theoretical spreading values are estimated at the point of interest using linear interpolation between existing nodes of the finite element mesh. The model also gives corresponding coefficients of friction.

Before using the model web properties must be computed. The thickness of the material was exceptionally hard to measure due to the rough nature of the web surface. However, a product of thickness and modulus is actually more important than their individual values. This product was computed from deflection equation (5.1). Thickness was estimated to be 0.002 inches and YOUNG's Modulus to be 20000.

$$\delta = (F*L)/(thickness*width*E) \tag{5.1}$$

TABLE 12

THEORETICAL MODEL INFORMATION SUMMARY

Web Width	17.1250
Web Thickness	0.002
Web Tension	1.0000
MD Poison's Ratio	0.3000
MD Young's Modulus	20000.0000
CD Young's Modulus	20000.0000
Entry Span	34.2500
Roller Base Radius	1.5000
Radius of Curvature	8000" or 4000"
Wrap Angle (deg)	90.0000
Bow Plane Angle (deg)	0, 45, or 90

TABLE 13

THEORETICAL SPREADING

Roller	**BPA**		
	0	45	90
CAR1 (Friction)	0.0036 (0.120)	0.0026 (0.125)	-0.0002 (0.118)
CAR2 (Friction)	0.0087 (0.227)	0.0053 (0.236)	-0.0003 (0.182)

Theoretical numbers were computed at node 85, which falls at a point 2.125 inches upstream of the spreader roller, of the finite element mesh representing the web. Absolute spreading is computed by subtracting the spreading at node 11, which is a point along the edge of the web about 34 inches upstream from the spreader roller, from that at node 85. Node 85 is the point at which experimental measurements were taken. Figure 39 shows part of the finite element mesh.

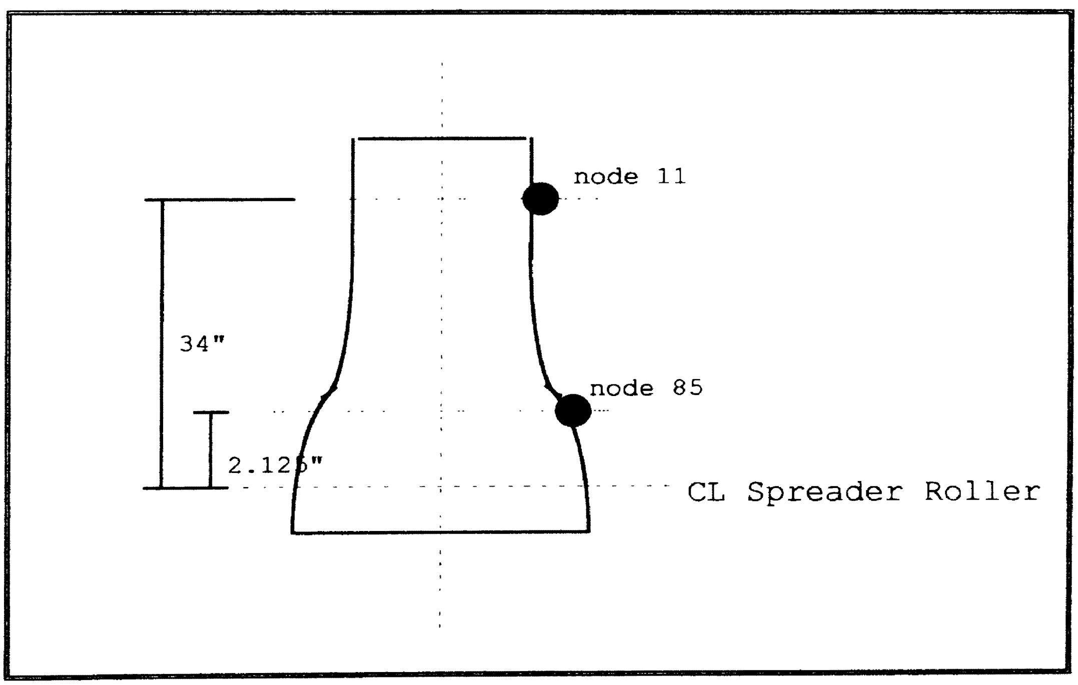

Figure 39. Finite element mesh (partial)

Measurements

Procedure

The experiment was conducted in few steps. First, the cylindrical roller was placed at the reference roller position. Measurements were taken in the following procedure. Move the sensors to the first location, advance the web until the point where we desire to take readings at is even with the sensors as described in chapter 4. Take the first width measurement. Then slowly move the sensors to the downstream location making sure that the setup is not highly disturbed. Advance the web until the desired point is again at the right level with respect to the markers on the sensors. Take the second width measurement. The difference between the two readings is the absolute width change, or spreading, as the web is displaced from point 1 to point 2. Repeat for all points using all three rollers. In case of spreader rollers, this procedure is also repeated for the different bow orientations shown in figure 40. The reason for this is to see how consistent experimental results and model predictions are with each other.

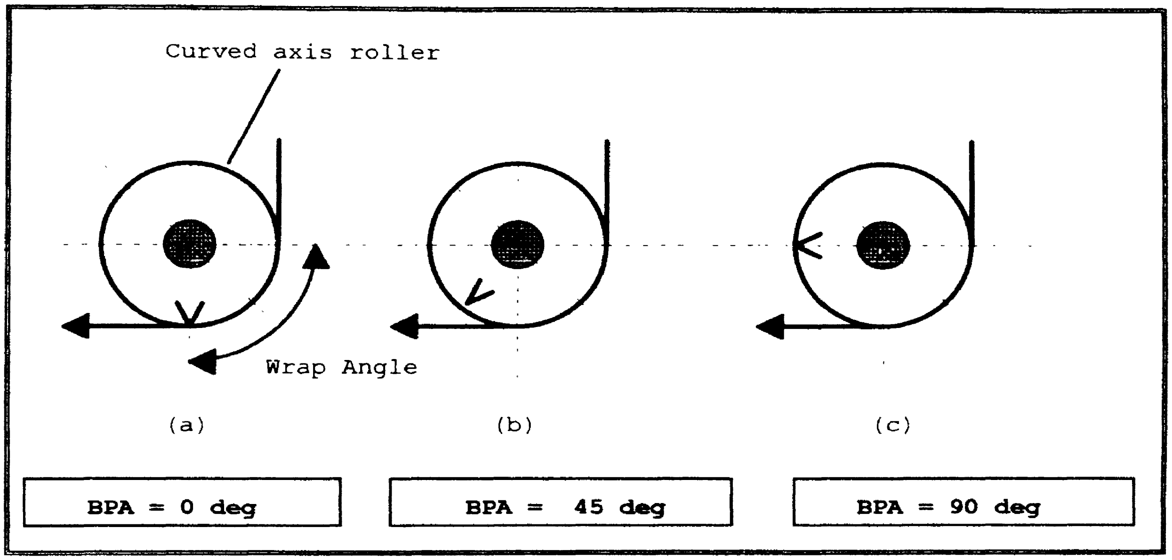

Figure 40. Different Bow Orientations

Repeatability

Repeatability of measurements is a very important part of this experiment. For one thing it means whether or not there is any consistency in the data taken. It also measures how well the setup can be returned to the same point over and over, especially with all the handling in between, and how well the sensors can measure the same width again and again. It is very obvious that human direct interface is critical however needs to be minimized in order to increase repeatability. Several repeatability test were conducted to ensure the efficiency and validity of the set up. One of these tests, **test1**, was to measure the width at one point then run the web around the loop and measure again. Do this several times without moving the sensors. Another test, **test2**, was to keep the web fixed this time and move the sensors back and forth while taking width values.

Repeatability criteria require these values to be the same or at least within close range. Tables 14 and table 15 show the results of the above two tests respectively.

TABLE 14

REPEATABILITY TEST1: FIXED SENSOR MOVING WEB

Run Number	**Sensor s1 (volts)**	**Sensor s2 (volts)**	**Width (inches)**
1	1.6910	2.9423	0.1996
2	1.6659	2.9678	0.1999
3	1.6427	2.9878	0.1999
4	1.6478	2.9771	0.1995

TABLE 15

REPEATABILITY TEST2: FIXED
WEB MOVING SENSOR

Run Number	Sensor s1 (volts)	Sensor s2 (volts)	Width (inches)
1	1.6811	2.9433	0.1996
2	1.6729	2.9678	0.1998
3	1.6423	2.9575	0.1997
4	1.6480	2.9564	0.1996

Results

Cylindrical Roller

The cylindrical roller was mainly used as a reference. Ideally, experimental measurements should indicate no web width changes. However, as shown in table 16 through table 18 that is not the case. These tables, representing measurements at **p1**, **p2**, and **p3** respectively, show that some changes in the width of the web are perceived. These changes average to about two thousands of an inch and are similar for all data points.

TABLE 16

CYLINDRICAL ROLLER RESULTS FOR p1

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.6910	0.0739	2.9423	0.1257	0.1996	
1	1	1.8290	0.0807	2.8684	0.1212	0.2019	0.0023
	0	1.6659	0.0726	2.9678	0.1272	0.1999	
2	1	1.7844	0.0785	2.9069	0.1235	0.2021	0.0022
	0	1.6427	0.0715	2.987	0.1284	0.1999	
3	1	1.7663	0.0777	2.9255	0.1246	0.2023	0.0024
	0	1.6478	0.0717	2.9771	0.1278	0.1995	
4	1	1.8290	0.0807	2.8684	0.1212	0.2019	0.0024

TABLE 17

CYLINDRICAL ROLLER RESULTS FOR p2

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8548	0.0820	3.0720	0.1337	0.2157	
1	1	1.9973	0.0890	2.9943	0.1289	0.2178	0.0021
	0	1.7823	0.0784	3.1252	0.1370	0.2155	
2	1	1.9123	0.0848	3.0584	0.1328	0.2177	0.0022
	0	1.8024	0.0794	3.1159	0.1365	0.2159	
3	1	1.9153	0.0850	3.0541	0.1326	0.2175	0.0016
	0	1.7988	0.0793	3.1095	0.1361	0.2153	
4	1	1.9471	0.0865	3.0370	0.1315	0.2180	0.0027

TABLE 18

CYLINDRICAL ROLLER RESULTS FOR p3

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8050	0.0796	2.7949	0.1169	0.1965	
1	1	1.9364	0.0860	2.7117	0.1121	0.1981	0.0017
	0	1.8052	0.0797	2.8315	0.1167	0.1964	
2	1	1.9007	0.0785	2.7483	0.1142	0.1984	0.0020
	0	1.8046	0.0792	2.8434	0.1177	0.1969	
3	1	1.8877	0.0836	2.7673	0.1153	0.1989	0.0020
	0	1.8050	0.0796	2.7949	0.1169	0.1965	
4	1	1.9372	0.0859	2.7120	0.1125	0.1984	0.0019

Curved Axis Rollers

CAR1 (curvature = 8000 inches)

Measurements using this spreader roller were taken for bow plane angles of 0, 45, and 90 degrees as previously mentioned. Results are given in table 19 through table 22 for the first case, table 23 through table 26 for the second, and table 27 through table 30 for the 90 degree bow plane angle case.

TABLE 19

CAR1 RESULTS FOR p1
BPA = 0 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.7699	0.0778	2.8980	0.1230	0.2004	
1	1	2.1091	0.0945	2.6812	0.1104	0.2049	0.0045
	0	1.7576	0.0772	2.8764	0.1217	0.2009	
2	1	2.1198	0.0950	2.6940	0.1101	0.2051	0.0042
	0	1.7374	0.0762	2.8886	0.1224	0.2006	
3	1	2.1096	0.0945	2.6810	0.1103	0.2048	0.0042
	0	1.7400	0.0764	2.8986	0.1230	0.2008	
4	1	2.0890	0.0935	2.7052	0.1117	0.2052	0.0044

TABLE 20

CAR1 RESULTS FOR p2
BPA = 0 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8862	0.0835	3.0258	0.1308	0.2143	
1	1	2.2381	0.1009	2.8001	0.1174	0.2183	0.0040
	0	1.9132	0.0849	3.0082	0.1297	0.2146	
2	1	2.2501	0.1015	2.7949	0.1169	0.2184	0.0038
	0	1.9034	0.0844	3.0070	0.1296	0.2140	
3	1	2.2658	0.1023	2.7825	0.1161	0.2185	0.0045
	0	1.8999	0.0842	3.0198	0.1302	0.2144	
4	1	2.2546	0.1018	2.7891	0.1165	0.2183	0.0039

TABLE 21

CAR1 RESULTS FOR p3
BPA = 0 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8488	0.0817	2.7462	0.1141	0.1958	
1	1	2.1851	0.0983	2.5098	0.1011	0.1994	0.0036
	0	1.8421	0.0814	2.7569	0.1147	0.1961	
2	1	2.1906	0.0985	2.5173	0.1015	0.2001	0.0040
	0	1.8420	0.0814	2.7571	0.1148	0.1962	
3	1	2.2071	0.0994	2.5074	0.1010	0.2004	0.0042
	0	1.8209	0.0803	2.7474	0.1144	0.1958	
4	1	2.1832	0.0980	2.5234	0.1019	0.1999	0.0041

Absolute spreading measurements are obtained by subtracting cylindrical roller from spreader roller measurements. Table 23 shows experimental absolute spreading measurements for BPA = 0. ***These spreading numbers are net values i.e. they already account for the cylindrical roller offset values.***

Table 22

CAR1 EXPERIMENTAL ABSOLUTE SPREADING MEASUREMENTS, BPA = 0 degrees

Point	Exper. Spreading	Theor. Spreading
1	0.0020	0.0036
2	0.0019	0.0036
3	0.0021	0.0036

The following tables summarize results for CAR1 with a BPA of 45 degrees.

Table 23

CAR1 RESULTS FOR p1
BPA = 45 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.7489	0.0768	2.9295	0.1239	0.2007	
1	1	2.0342	0.0908	2.7424	0.1138	0.2046	0.0039
	0	1.7394	0.0764	2.9270	0.1247	0.2001	
2	1	2.0281	0.0905	2.7381	0.1136	0.2043	0.0041
	0	1.7273	0.0757	2.9217	0.1244	0.2011	
3	1	2.0351	0.0908	2.7355	0.1134	0.2043	0.0042
	0	1.7634	0.0775	2.9255	0.1246	0.2021	
4	1	2.0615	0.0921	2.7477	0.1141	0.2063	0.0041

Table 24

CAR1 RESULTS FOR p2
BPA = 45 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	1.8827	0.0834	3.0645	0.1321	0.2155	
1	1	2.1801	0.0980	2.8637	0.1209	0.2189	0.0034
	0	1.8815	0.0833	3.0409	0.1317	0.2150	
2	1	2.1961	0.0988	2.8523	0.1202	0.2190	0.0040
	0	1.8719	0.0828	3.0543	0.1326	0.2154	
3	1	2.1879	0.0984	2.8672	0.1211	0.2195	0.0041
	0	1.8947	0.0840	3.0433	0.1319	0.2159	
4	1	2.2184	0.0999	2.8484	0.1200	0.2199	0.0041

Table 25

CAR1 RESULTS FOR p3
BPA = 45 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	1.7963	0.0791	2.8063	0.1175	0.1967	
1	1	2.1036	0.0942	2.6025	0.1061	0.2003	0.0036
	0	1.8226	0.0804	2.7769	0.1158	0.1962	
2	1	2.1194	0.0950	2.5764	0.1046	0.1996	0.0034
	0	1.8189	0.0802	2.7943	0.1168	0.1971	
3	1	2.1204	0.0950	2.5898	0.1054	0.2004	0.0033
	0	1.8299	0.0808	2.7956	0.1169	0.1977	
4	1	2.1517	0.0966	2.5680	0.1042	0.2008	0.0031

TABLE 26

CAR1 EXPERIMENTAL ABSOLUTE SPREADING
MEASUREMENTS, BPA = 45 degrees

Point	Exper. Spreading	Theor. Spreading
1	0.0018	0.0026
2	0.0018	0.0026
3	0.0015	0.0026

The following tables summarize results for CAR1 with a BPA of 90 degrees.

TABLE 27

CAR1 RESULTS FOR p1
BPA = 90 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	1.7286	0.0762	2.9528	0.1263	0.2025	
1	1	1.9831	0.0883	2.7819	0.1161	0.2044	0.0019
	0	1.7292	0.0758	2.9601	0.1267	0.2026	
2	1	1.9864	0.0884	2.7882	0.1165	0.2049	0.0023
	0	1.7382	0.0763	2.9490	0.1261	0.2023	
3	1	1.9970	0.0890	2.7772	0.1158	0.2048	0.0025
	0	1.7319	0.0759	2.9546	0.1264	0.2024	
4	1	2.0119	0.0897	2.7886	0.1150	0.2047	0.0023

TABLE 28

CAR1 RESULTS FOR p2
BPA = 90 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8806	0.0833	3.0703	0.1336	0.2169	
1	1	2.1490	0.0964	2.8787	0.1218	0.2183	0.0014
	0	1.8688	0.0827	3.0709	0.1336	0.2163	
2	1	2.1487	0.0964	2.8838	0.1221	0.2185	0.0022
	0	1.8780	0.0831	3.0720	0.1337	0.2168	
3	1	2.1462	0.0963	2.8959	0.1228	0.2192	0.0023
	0	1.8827	0.0834	3.0704	0.1334	0.2168	
4	1	2.1552	0.0968	2.8843	0.1226	0.2184	0.0012

TABLE 29

CAR1 RESULTS FOR p3
BPA = 90 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8044	0.0795	2.8124	0.1179	0.1974	
1	1	2.0757	0.0928	2.6180	0.1069	0.1997	0.0023
	0	1.8252	0.0806	2.8092	0.1177	0.1983	
2	1	2.0743	0.0928	2.6144	0.1067	0.1995	0.0012
	0	1.8096	0.0798	2.8120	0.1179	0.1976	
3	1	2.1058	0.0943	2.6136	0.1067	0.1996	0.0020
	0	1.8049	0.0796	2.8225	0.1175	0.1981	
4	1	2.0916	0.0936	2.6110	0.1061	0.1997	0.0016

TABLE 30

CAR1 EXPERIMENTAL ABSOLUTE SPREADING MEASUREMENTS, BPA = 90 degrees

Point	**Exper. Spreading**	**Theor. Spreading**
1	-0.0001	-0.0002
2	-0.0004	-0.0002
3	-0.0001	-0.0002

CAR2 (curvature = 4000 inches)

Measurements were taken for bow plane angles of 0, 45, and 90 degrees as previously mentioned. Results are given in table 31 through table 34 for the first case, table 35 through table 38 for the second, and table 39 through table 42 for the 90 degree bow plane angle case.

TABLE 31

CAR2 RESULTS FOR p1
BPA = 0 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8877	0.0836	2.8310	0.1190	0.2026	
1	1	2.377	0.1081	2.4583	0.0985	0.2066	0.0040
	0	1.8802	0.0833	2.8631	0.1209	0.2041	
2	1	2.3656	0.1075	2.4986	0.1006	0.2080	0.0039
	0	1.8407	0.0813	2.8623	0.1208	0.2022	
3	1	2.3423	0.1063	2.4859	0.0999	0.2062	0.0040
	0	1.8590	0.0822	2.8753	0.1216	0.2038	
4	1	2.3409	0.1062	2.4984	0.1006	0.2067	0.0029

TABLE 32

CAR2 RESULTS FOR p2
BPA = 0 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	2.2691	0.1025	2.7111	0.1121	0.2146	
1	1	2.7615	0.1292	2.3011	0.0908	0.2200	0.0055
	0	2.1908	0.0985	2.7619	0.1150	0.2135	
2	1	2.7087	0.1262	2.3330	0.0923	0.2185	0.0050
	0	2.2289	0.1005	2.7676	0.1153	0.2157	
3	1	2.7126	0.1264	2.3698	0.0941	0.2205	0.0048
	0	2.2036	0.0992	2.7929	0.1167	0.2159	
4	1	2.7148	0.1266	2.3759	0.0944	0.2209	0.0050

TABLE 33

CAR2 RESULTS FOR p3
BPA = 0 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	2.1854	0.0983	2.4673	0.0990	0.1972	
1	1	2.6656	0.1238	2.0049	0.0771	0.2009	0.0037
	0	2.1587	0.0969	2.5042	0.1009	0.1978	
2	1	2.6243	0.1214	2.0934	0.0811	0.2026	0.0048
	0	2.1467	0.0963	2.5318	0.1023	0.1986	
3	1	2.6301	0.1218	2.0743	0.0803	0.2020	0.0034
	0	2.1229	0.0952	2.5323	0.1023	0.1975	
4	1	2.6014	0.1202	2.0882	0.0809	0.2011	0.0036

Absolute spreading measurements are obtained by subtracting cylindrical roller results from spreader roller measurements. Table 34 shows experimental absolute spreading measurements and their percentage errors for CAR2 at BPA = 0.

TABLE 34

CAR2 EXPERIMENTAL ABSOLUTE SPREADING MEASUREMENTS, BPA = 0 degrees

Point	Exper. Spreading	Theor. Spreading
1	0.0014	0.0087
2	0.0029	0.0087
3	0.0020	0.0087

TABLE 35

CAR2 RESULTS FOR p1
BPA = 45 degrees

Test	Pos.	s1		s2		Width	Spread
		volts	inches	volts	inches		
	0	1.8357	0.0811	2.8831	0.1221	0.2031	
1	1	2.4007	0.1093	2.4299	0.0971	0.2064	0.0032
	0	1.8566	0.0821	2.8726	0.1214	0.2035	
2	1	2.4027	0.1094	2.4363	0.0974	0.2068	0.0033
	0	1.8827	0.0834	2.8690	0.1212	0.2046	
3	1	2.4168	0.1102	2.4419	0.0977	0.2078	0.0032
	0	1.8410	0.0813	2.8932	0.1227	0.2040	
4	1	2.3902	0.1088	2.4404	0.0976	0.2064	0.0024

TABLE 36

CAR2 RESULTS FOR p2
BPA = 45 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	2.2243	0.1002	2.7706	0.1155	0.2157	
1	1	2.7606	0.1292	2.3191	0.0916	0.2208	0.0051
	0	2.2219	0.1001	3.7952	0.1169	0.2170	
2	1	2.7602	0.1292	2.3151	0.0914	0.2206	0.0036
	0	2.2237	0.1002	3.8030	0.1173	0.2175	
3	1	2.7425	0.1282	2.3014	0.0908	0.2189	0.0014
	0	2.2132	0.0997	2.8135	0.1179	0.2176	
4	1	2.7546	0.1288	2.3196	0.0917	0.2205	0.0029

TABLE 37

CAR2 RESULTS FOR p3
BPA = 45 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	2.1448	0.0962	2.5637	0.1040	0.2002	
1	1	2.6150	0.1209	2.0719	0.0802	0.2011	0.0009
	0	2.1422	0.0961	2.5481	0.1031	0.1993	
2	1	2.6727	0.1242	2.0276	0.0781	0.2023	0.0030
	0	2.1535	0.0961	2.5402	0.1027	0.1994	
3	1	2.6676	0.1242	2.0276	0.0791	0.2030	0.0036
	0	2.1355	0.0961	2.5469	0.1031	0.1984	
4	1	2.6534	0.1231	2.0486	0.0791	0.2022	0.0038

TABLE 38

CAR2 EXPERIMENTAL ABSOLUTE SPREADING MEASUREMENTS, BPA = 45 degrees

Point	Exper. Spreading	Theor. Spreading
1	0.0007	0.0053
2	0.0011	0.0053
3	0.0009	0.0053

TABLE 39

CAR2 RESULTS FOR p1
BPA = 90 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	1.8119	0.0799	2.9244	0.1246	0.2045	
1	1	2.2854	0.1033	2.4163	0.0963	0.1996	-0.0049
	0	1.8349	0.0810	2.9269	0.1247	0.2057	
2	1	2.3112	0.1047	2.4262	0.0969	0.2015	-0.0042
	0	1.8247	0.0805	2.9214	0.1244	0.2049	
3	1	2.2977	0.1040	2.4334	0.972	0.2012	-0.0037
	0	1.8093	0.0798	2.9264	0.1247	0.2045	
4	1	2.2950	0.1038	2.4145	0.0963	0.2001	-0.0043

TABLE 40

CAR2 RESULTS FOR p2
BPA = 90 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	2.1862	0.0983	2.8262	0.1187	0.2170	
1	1	2.6630	0.1236	2.2893	0.0902	0.2138	-0.0032
	0	2.1911	0.0986	2.8478	0.1200	0.2185	
2	1	2.6797	0.1246	2.3037	0.0909	0.2155	-0.0031
	0	2.1303	0.0955	2.8465	0.1199	0.2154	
3	1	2.6559	0.1246	2.2971	0.0906	0.2138	-0.0016
	0	2.1830	0.0981	2.8353	0.1192	0.2174	
4	1	2.6861	0.1249	2.2924	0.0904	0.2153	-0.0021

TABLE 41

CAR2 RESULTS FOR p3
BPA = 90 degrees

Test	Pos.	s1 volts	s1 inches	s2 volts	s2 inches	Width	Spread
	0	2.1014	0.0941	2.5968	0.1057	0.1998	
1	1	2.5959	0.1199	2.0534	0.0793	0.1992	-0.0007
	0	2.1180	0.0949	2.5953	0.1057	0.2006	
2	1	2.6110	0.1207	2.0359	0.0785	0.1992	-0.0014
	0	2.1490	0.0964	2.5935	0.1056	0.2020	
3	1	2.6090	0.1206	2.0457	0.0790	0.1995	-0.0025
	0	2.1276	0.0954	2.6084	0.1064	0.2018	
4	1	2.6046	0.1203	2.0606	0.0796	0.2000	-0.0018

TABLE 42

CAR2 EXPERIMENTAL ABSOLUTE SPREADING MEASUREMENTS, BPA = 90 degrees

Point	**Exper. Spreading**	**Theor. Spreading**
1	-0.0066	-0.0003
2	-0.0048	-0.0003
3	-0.0039	-0.0003

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Calibration

The calibration of the sensors was performed using a high precision micrometer with 0.0001 inch precision. The reason for this high precision is to be able to accurately measure spreading values which were as low as a thousand of an inch. For each sensor a calibration cubic spline curve was obtained. This was required in order to accurately predict absolute position displacements of the web. It was shown that removed points from the Calibration curve can be recomputed to within less than 0.0006 from their actual displacements for sensor s1 and 0.0008 for sensor s2. It was also shown that as the gap between missing points is increased the error increased by an average factor of 5.5 as well. From which it was deduced that if this gap is halved the error could be reduced by that same factor, hence, absolute position could be computed within a few thousandths of an inch.

Spreading Measurements

In chapter 5 it was shown that experimental results agree with theoretical predictions as far as spreading behavior is concerned. The use of spreader rollers definitely resulted in web width changes. This width increase or decrease was dependent on bow orientation and size.

For the cylindrical roller the average width change was 0.002125. This was regarded as a measurement offset and was accounted for when using spreader rollers, by subtracting this spread from curved axis roller one.

For spreader rollers three bow plane angles, 0, 45, and 90 degrees, were tested. Web spreading values for these orientation respectively averaged 0.001993, 0.001648, and -0.000194 for **CAR1** and 0.002092, 0.0009083, and -0.0051167 for **CAR2**. Results from **CAR1** show behavior that is consistent with the respective theoretical values. Percentage errors range from 2.1% to 45%. Results from **CAR2** are very non consistent and at times unpredictable. In fact, a defect was found in this roller when it was returned to the manufacturer for re inspection.

Recommendations

For future elaboration on this experiment, a wider web may be used. This will increase traction between the web and the roller and in turn increase the spreading.

Another definite area that needs further elaboration is the positioning of the sensors with respect to the web. The experiment requires that the sensors have the same position with respect to the web at both upstream and downstream locations. I recommend the use of a laser based setup to achieve this alignment accurately.

Finally, human interface may also be reduced by automatically advancing the sensors as well as the web.

BIBLIOGRAPHY

1. Delahoussaye, R. D., " Analysis Of Deformations, Stresses And Forces In Webs Encountering Spreading Rollers". Ph.D. Thesis Oklahoma State University, Stillwater, Oklahoma, 1989.

2. Taecheol, Kim, " Precision Position Measurement Of The Web Edge Using The He-Ne Laser" Masters Thesis Oklahoma State University, Stillwater, Oklahoma, 1990.

3. Howard, C. Robert, " Mechanical Measurements By Electrical Methods". First Edition 1946.

4. Sirohi, R. S., And Krishona, H. C. Radha. " Mechanical Measurements"

5. Beckwith, T. G., And Buck N. Lewis. " Mechanical Measurements ". Ed. Massachusetts: Addison-Wesley Publishing Company, 1969.

6. Moore, B. Mark. " Theory And Application Of Mechanical Engineering Measurements". 1960.

7. Gronquist, D. "Sensors And Signal Processing. An Optical Edge Sensor For Transparent Film Applications". Fife Corporation. 1992.

8. "Applied Roller Technology" Company manual. Charlotte, North Carolina.

9. "Sensor" From FIFE corporation. Oklahoma City, Oklahoma.

APPENDIX : - COMPUTER CODE

C code :

```
/*****************************************************/
/****                                            ****/
/****          WEB SPREADING ANALYSIS            ****/
/****                                           ****/
/*****************************************************/

#include <math.h>
#include <stdlib.h>
#include <stdio.h>
#include <graphics.h>
#include <conio.h>
#include <dos.h>
#include "nr.h"
#include "nrutil.h"

#define BASE      0x300  /* ADC16 Board Base Adress    */
#define DATREG    BASE   /* Data Register Adress       */
#define LDATREG   BASE+1 /* Data Register Adress       */
#define MUXGREG   BASE+2 /* MUX/Gain Adress            */
#define STATREG   BASE+3 /* Status Register Adress     */
#define CMDMSK    0x80
#define MAXCH     8     /* Maximum number of channels */
#define NP        8
#define STRING    80
#define BIG       1e31
#define TRUE     1
#define NMAX      30

void get_spline();
int n;
main()
{
/*****************************************************/
/****                                             */
/****   Variables:                                */
/****     The important variables in this code are:  */
/****                                             */
/****       pos : is the position of the web with    */
/****             respect to either               */
/****             sensor. pos=pos_a for sensora,     */
/****             and pos=pos_b for sensorb.         */
/****                                            */
/****     width : is the width of the web         */
/****    pwidth : is the width of the web            */
```

```
/****                at position = count                */
/**** spreading : spreading of the web between          */
/****                position = count                   */
/****                and position = 0.                  */
/****                                                   */
/*******************************************************/

float                *xa,*ya,*y2a,*xb,*yb,*y2b;
float                yp1=BIG,ypn=BIG,pos_a,pos_b,pos;
int                  i,sensora=3,sensorb=2;
int                  numch=1, count, k, counter;
unsigned char        channel,zero=0;
                  /* Start at channel=0, gain=1  */
unsigned char        low_byte, high_byte, overrange,
stat;
float                reading,readinga,readingb,width;
float                pwidth[NMAX],spreading[NMAX];
int                  again=TRUE, restart=TRUE;
char                 outfilename[80];
char                 text[200];
FILE                 *out;

while(restart == TRUE)
     {
     /**** open output file ****/
     printf("\n Enter Output File Name : ");
     scanf("%s",outfilename);
     out=fopen(outfilename,"w");
/**     printf("\n Enter Run Information :");
     scanf("%s",text);
**/
     xa=vector(1,NP);
     ya=vector(1,NP);
     y2a=vector(1,NP);
     xb=vector(1,NP);
     yb=vector(1,NP);
     y2b=vector(1,NP);

     get_spline(sensora,xa,ya,yp1,ypn,y2a);
         /** this is done only once at **/
     get_spline(sensorb,xb,yb,yp1,ypn,y2b);
         /** the beginning of each run **/

      /**** This portion of the program reads from the
ADC16 board ****/
```

```
      fprintf(out,"\n Web Width And Spreading
Measurements : \n");
      fprintf(out," ============================\n\n");
/*      fprintf(out,"%s\n\n",text);    */
      fprintf(out,"%24s %18s\n","Sensor a","Sensor b");
      fprintf(out,"%8s %9s %8s %9s %8s %12s %17s \n\n",
"Position",   "Voltage", "Inches", "Voltage", "Inches",
"Web Width", "Web  Spreading");

      count=0;
      pos=0.0;
      pos_a=pos_b=0.0;
      width=0.0;
      spreading[0]=0.0;
      textattr(14);

      while(CMDMSK & inportb(STATREG));       /* While
Board isn't Busy */
      again=TRUE;
      while(again==TRUE)
      {
      counter=0;
      clrscr();
      do{
     gotoxy(1,5);
     cprintf("\n%15s %22s %22s\n", "channel #","Reading
in volts","Reading in inches");

     for(channel=0;channel<=numch;channel++)
                                   /* While not Done  */
      {
      outportb(MUXGREG, channel*8);
                             /* Write Channel Number   */
      delay(20);
                             /* Let amplifier settle   */
      outportb(DATREG, zero);
                             /* Start A/D Conversion   */
      while(CMDMSK & inportb(STATREG));
      outportb(STATREG,0x40);
                                   /* Set Overrange    */
      overrange = inportb(DATREG);
      if(CMDMSK & inportb(DATREG))
        printf("\n OOps !! OVER RANGE on channel %d
equal to %4u\n\n", channel, overrange);
      outportb(STATREG,zero);
                             /* Reset Overrange bit    */
```

```
      low_byte = inportb(LDATREG);
      high_byte = inportb(DATREG);
      high_byte = (high_byte & 0x7f);
      reading = ((256 * high_byte) +
low_byte)*5.0/32767;
      switch(channel){
          case 0:
               readinga=reading;
               splint(xa,ya,y2a,NP,readinga,&pos_a);
               pos=pos_a;
               break;
          case 1:
               readingb=reading;
               splint(xb,yb,y2b,NP,readingb,&pos_b);
               pos=pos_b;
               break;
             }
      printf("\n%12d %20.4f %20.4f",channel, reading,
pos);

     }
     /**** This concludes one A/D conversion for each
channel ****/
     /**** Now compute width ****/

     width = pos_a+pos_b;

     gotoxy(4,12);
     cprintf("The web width is : %12.4f inches
\n\n",width);
     if(count > 0)
     {
     spreading[count]=width-pwidth[0];
     gotoxy(4,13);
     cprintf("\nThe spreading is : %12.5f
inches",spreading[count]);
     }
     gotoxy(10,18);
     cprintf(" Hit space_bar to stop ... \r\n");
     }while(!kbhit());
     pwidth[count]=width;
     fprintf(out,"%4d %12.4f %9.4f %8.4f %9.4f %10.4f
%16.4f\n",count,readinga,pos_a,readingb,pos_b,pwidth[co
unt],spreading[count]);
     cprintf("\n\nDo you want to run again ? (1 for
yes/0 for no) : ");
```

```
      scanf("%d",&again);
      count++;
      }
      /**** Compute spreading ****/

      fclose(out);
      free_vector(y2b,1,NP);
      free_vector(yb,1,NP);
      free_vector(xb,1,NP);
      free_vector(y2a,1,NP);
      free_vector(ya,1,NP);
      free_vector(xa,1,NP);
      textcolor(15);
      printf("\n\nDo You Want To Restart ? ");
      printf("\nEnter 1 For Yes ---> ");
      scanf("%d",&restart);
      }
      return 0;
}

/**** Function get_spline returns the second
      derivative vector for the given sensor ****/

void get_spline(sensor,x,y,yp1,ypn,y2)
float x[],y[],y2[],yp1,ypn;
int   sensor;
{
     int   i;
     float x0,y0,y20;
     FILE  *ifp;


     /* Read data for interpolation */
     switch(sensor){
          case 1:
               ifp = fopen("s1_cal.dat","r");
               break;
          case 2:
               ifp = fopen("s2_cal.dat","r");
               break;
          case 3:
               ifp = fopen("s3_cal.dat","r");
               break;
          case 4:
               ifp = fopen("s4_cal.dat","r");
               break;
```

```
        }

        i=1;
        while(fscanf(ifp,"%f%f%f\n",&x0,&y0,&y20)==3)
              {
              y[i]=x0;
              x[i]=y0;
              y2[i]=y20;
              i=i+1;
              }
        n=i-1;

        /**** Get spline second derivatives ****/

    fclose(ifp);
}

              /********** END **********/
```

VITA

Fitouri B. Salah Hnainia

Candidate for the Degree of

Master of Science

Thesis: WEB SPREADING MEASUREMENT USING PHOTOELECTRIC SENSOR

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Sfax, Tunisia, July 16, 1966, the son of Salah and Aisha Hnainia.

Education: Graduated from Mahares High School, Sfax, Tunisia, 1986; received Bachelor of Science Degree in Mechanical Engineering from Oklahoma State University at Stillwater in May, 1990; Completed requirements for the Master of Science Degree at Oklahoma State University in May, 1993.

Professional Experience: Teaching Assistant, Departement of Mechanical Engineering, Oklahoma State University, August, 1990, to May, 1993.