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To the Graduate Council:

I am submitting herewith a thesis written by Nicholas M. Sullivan entitled "Developing a Feedback Control System Using Electromagnets to Increase the Stiffness of a Circular Saw Blade." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

Frank H. Speckhart, Major Professor

We have read this thesis and recommend its acceptance:

William R. Hamel, J. A. M. Boulet

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Accepted for the Council:

Vice Chancellor and Dean of Graduate Studies

Thesis
2004
.S93

Developing a Feedback Control System Using Electromagnets to Increase the Stiffness of a Circular Saw Blade

A Thesis Presented
for the Master of Science Degree
The University of Tennessee, Knoxville

Nicholas M. Sullivan
May 2004

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I would like to thank everyone that has helped me complete my Master of Science Degree in Mechanical Engineering. I would specifically like to thank Dr. Frank H. Speckhart for the opportunity to work on this research project and Dennis W. Higdon for his guidance and knowledge.

Most importantly, I would like to thank my wife for all of her encouragement and support throughout the whole process. She is my motivation.

Abstract

This document covers the research performed in developing a feedback control system using electromagnets to increase the stiffness of a circular saw blade. A finite element analysis was performed on a model of a saw blade to determine where the electromagnets should be placed relative to the saw blade. Experimental tests were performed with each component of the system to determine their characteristics. A mathematical model of the complete feedback control system was developed in Simulink. Various tests were performed to determine what parameters could be changed in order to get the desired response out of the system. A prototype of the system was designed and built. Tests were run with the prototype to determine the effectiveness of the feedback control system

Table of Contents

Chapter **Page**

1 Introduction 1
1.1 Project Objective 2
1.2 Previous Research 2
1.3 General Approach 2
2 Finite Element Analysis 4
2.1 Assumptions 4
2.2 Background 5
2.3 Creating A Circular Saw Blade Model 5
2.4 How a Circular Saw Blade Bends 7
2.5 Reducing the Deflection 8
2.6 Conclusions 11
3 System Components 12
3.1 Sensor 12
Voltage versus Distance 12
Conclusions 14
3.2 Electromagnets 15
Power 15
Magnetic Force 15
Time Constant 21
Results 23
Conclusions 23
3.3 Saw Blades 23
Test Jig 24
Natural Frequency 24
Equivalent Stiffness 25
Conclusions 29
4 Mathematical Model 31
4.1 Saw Blade 32
4.2 Sensor 34
4.3 Controller 34
4.4 Power Supply 36
4.5 Electromagnets 37
4.6 Conclusions 40
5 Testing of Mathematical Model 41
5.1 Parameters 41
5.2 Ramped Input 42
5.3 Step Input 44
5.4 Conclusions 46
6 Prototype Design 47

6.1 Control System 47
Proximity Transducer System 47
Bipolar Operational Power Supply 47
Electromagnets 48
6.2 Mounting 49
6.3 Conclusions 49
7 Testing of Prototype 52
7.1 Experimental 52
Setup 52
Procedure 52
7.2 Results 53
7.3 Conclusions 55
8 Conclusions 57
8.1 Results 57
8.2 Future Considerations 58

List of References 60
Vita 62

List of Tables

Tables **Page**

Table 2-1 Design Space Parameters Used for Finite Element Analysis 5
Table 2-2 General Dimensions of Circular Saw Blade Models 6
Table 3-1 Experimental Values of C_i and r_i in the Magnetic Force Equation 19
Table 3-2 Saw Blades Lowest Natural Frequencies 27
Table 3-3 Equivalent Stiffness of Circular Saw Blades 30
Table 5-1 Parameters Used for Testing of Mathematical Model 42
Table 7-1 Stiffness of 0.052" Thick Saw Blade with Control System 55
Table 7-2 Equivalent Thickness of 0.052" Thick Saw Blade with Feedback Control System 56
Table 8-1 Equivalent Stiffness of 0.052" Thick Circular Saw Blade With and Without Feedback Control System 57
Table 8-2 Equivalent Thickness of a 0.052" Thick Circular Saw Blade with the Feedback Control System 58

List of Figures

Figures **Page**

Figure 1-1 Comparison of Saw Dust Produced from Two Saw Blades of Different Thickness[1] 1
Figure 1-2 General Structure of the Feedback Control System 2
Figure 2-1 Point Where External Load is Applied to Circular Saw Blade Causing it to Bend 4
Figure 2-2 Circular Saw Blade Models Used for Finite Element Analysis 6
Figure 2-3 Force Applied Perpendicular to the Plane of the Saw Blade Model 7
Figure 2-4 Deflection of Saw Blade Model Due to an External Force of 1 lb Applied at the Outer Edge 8
Figure 2-5 Maximum Deflection versus the Magnitude of the Applied Force 9
Figure 2-6 Radial Line where Force 2 was Applied to Blade01 10
Figure 2-7 Forces Applied to Blade01 to Reduce the Deflection 10
Figure 2-8 Maximum Displacement versus the Radial Distance that the Opposing Force was Applied 11
Figure 3-1 Method Used to Determine the Voltage versus Distance Relationship of the Proximity Transducer System 13
Figure 3-2 Output Voltage of Proximity Probe versus the Distance 13
Figure 3-3 Output Voltage of Proximity Probe versus Distance within the Linear Range 14
Figure 3-4 Surface Temperature of Electromagnet versus Time with 2.5 Amps 16
Figure 3-5 Test Used to Measure the Magnetic Force Produced from the Electromagnets 18
Figure 3-6 Magnetic Force versus the Current and Distance 19
Figure 3-7 The Function C(i) in the Magnetic Force Equation 20
Figure 3-8 The Function r(i) in the Magnetic Force Equation 20
Figure 3-9 Circuit Used to Determine Time Constant of Electromagnet 22
Figure 3-10 Model Used to Determine Time Constant of Electromagnet 22
Figure 3-11 Simulated Voltage across Resistor R2 versus Time 24
Figure 3-12 Jig Used for Holding Saw Blade throughout Natural Frequency and Stiffness Test 25
Figure 3-13 Frequency Content of 0.052" Thick Circular Saw Blade 26
Figure 3-14 Frequency Content of 0.065" Thick Circular Saw Blade 26
Figure 3-15 Weights Hanging from Saw Blade to Determine Equivalent Stiffness 28
Figure 3-16 Force versus the Displacement of the Circular Saw Blades 29
Figure 4-1 Feedback Control System Modeled in Simulink 31
Figure 4-2 Spring-Mass-Damper System Used to Represent the Saw Blade 32
Figure 4-3 Mathematical Model of the Saw Blade 33
Figure 4-4 Sub-System Used to Represent the Saw Blade Model 33
Figure 4-5 Mathematical Model of the Sensor 34
Figure 4-6 Sub-system Used to Represent the Sensor 35
Figure 4-7 Mathematical Model of Proportional Controller 35
Figure 4-8 Sub-System Used to Represent the Proportional Controller 35

Figure 4-9 Mathematical Model of the Power Supply 36
Figure 4-10 Sub-System Used to Represent the Power Supply 37
Figure 4-11 Mathematical Model of One Electromagnet 38
Figure 4-12 Sub-System Used to Represent One Electromagnet 38
Figure 4-13 Mathematical Model Used to Represent Two Electromagnets 39
Figure 4-14 Sub-System Representation of Both Electromagnets 39
Figure 4-15 Complete Mathematical Model of the Feedback Control System 40
Figure 5-1 Mathematical Model of the Feedback Control System 41
Figure 5-2 Force versus Displacement of 0.052" Saw Blade with Kp and t Equal to Zero 43
Figure 5-3 Force versus Displacement with Various Combinations of Kp and *t* 43
Figure 5-4 Stiffness of Saw Blade with Various Values of Kp when the Time Constant of the Electromagnets is Zero 44
Figure 5-5 Displacement of Saw Blade to a Unit Step Input without Control System 45
Figure 5-6 Displacement of Saw Blade to a Unit Step Input with Control System On 45
Figure 6-1 General Structure of the Feedback Control System Used on Prototype 47
Figure 6-2 Simplified Diagram of the BOP 48
Figure 6-3 Circuit Diagram Used to Connect the Electromagnets to the BOP 49
Figure 6-4 Bracket Designed to Mount Electromagnets and Proximity Probe on Table Saw 50
Figure 6-5 Assembly View of the Electromagnet Mount 50
Figure 6-6 Prototype of Feedback Control System on Table Saw 51
Figure 7-1 Mounting of Electromagnets and Proximity Probe on Table Saw 52
Figure 7-2 Force Gage was Used to Apply an External Force on Saw Blade 53
Figure 7-3 Force versus Displacement for 0.052" Thick Saw Blade With and Without Feedback Control 54
Figure 7-4 Stiffness Comparison of 0.065" Thick Saw Blade without Feedback Control and 0.052" Saw Blade with Feedback Control 56

1 Introduction

The price of raw materials has escalated yearly and the wood industry has looked for ways to increase yield. One solution has been to reduce wastes by using thin kerf saw blades.

Anytime a piece of material is cut with a saw blade, there is wasted material in the form of sawdust. The amount of sawdust produced depends on the kerf of the saw blade. The kerf of a saw blade is the width of the gap left in the material from the saw blade passing through it. The thinner the kerf, the less saw dust produced as shown in Figure 1-1.

The kerf of a saw blade does not have to be reduced a significant amount to have an impact in increasing yield. Morris Stephens of Armstrong Flooring commented:

> *"A few thousandths of an inch may not seem like much until multiplied by the literally millions of board feet of lumber we process each year. It adds to the bottom line."*

Along with the benefits of using thin kerf saw blades, there are problems associated with them. One of the main problems is that thin kerf saw blades have a hard time cutting within a desired tolerance. The reduction in the thickness of the saw blade body makes the saw blades less stiff. The resulting cut may be unacceptable. Therefore, the minimum kerf is limited by the stiffness of the saw blades.

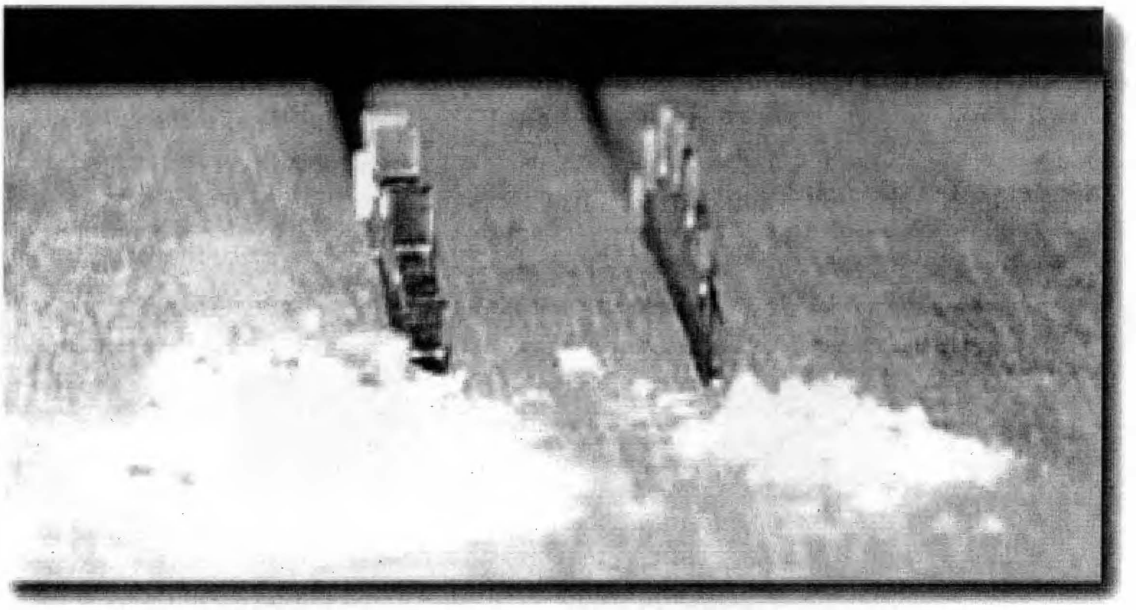


Figure 1-1 Comparison of Saw Dust Produced from Two Saw Blades of Different Thickness[1]

1.1 PROJECT OBJECTIVE

The objective of this research project was to develop a feedback control system to increase the stiffness of a circular saw blade. Within the feedback control system, electromagnets would be used to apply external forces on a circular saw blade in a manner to oppose any bending. The ideal feedback control system would allow a thin kerf saw blade to bend less while cutting and produce less wasted material.

1.2 PREVIOUS RESEARCH

After completing a literature search, using relatively thin circular saw blades to increase yield is not new to the wood industry. The majority of research has been aimed towards reducing the build up of heat within the saw blade body. Various methods such as changing the geometry of the saw blade and adding temperature sensors have been used in attempt to control the distribution of heat. However, there was no evidence that electromagnets have been used to increase the stiffness of a circular saw blade.

1.3 GENERAL APPROACH

The general structure of the feedback control system is shown in Figure 1-2. A sensor was used to measure the displacement of the saw blade. A proportional controller determined how much power the electromagnets received. The electromagnets were used to pull on the saw blade in order to make the displacement of the saw blade zero.

The first step in developing the feedback control system was to determine where to place the electromagnets relative to the circular saw blade. Tests were performed on a circular saw blade model within a finite element software, Design Space. The results from the tests were used to determine where an external force could be applied to the circular saw blade model to increase the stiffness.

Experiments were then performed on the components of the feedback control system. Known inputs were applied to each component, and their outputs were recorded. The experimental data was used to define mathematical formulas that described the behavior of each component.

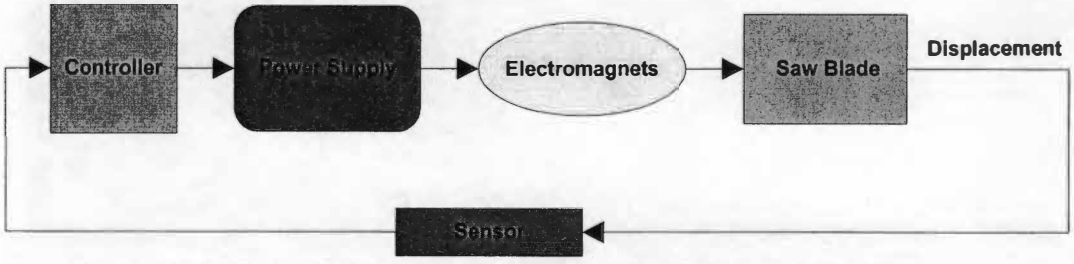


Figure 1-2 General Structure of the Feedback Control System

Simulink was then used to create a mathematical model of the system. Individual models of each component were developed. The models were tested to verify that they worked properly. They were then combined to form a complete feedback control system. Simulations were run as the parameters of the system were varied. The objective was to understand the affect of each parameter on the output of the system.

A prototype of the feedback control system was then designed and built based on the previous experiments. A table saw was used to test the feedback control system to determine the systems effectiveness in increasing the stiffness of the circular saw blade.

2 Finite Element Analysis

The finite element software, Design Space, was used to determine where to put the electromagnets relative to the saw blade. The objective was to make a saw blade model bend and determine where external forces could be applied to reduce the bending. Wherever the forces reduced the bending the most is where the electromagnets would be placed on the prototype.

2.1 ASSUMPTIONS

Many factors cause a circular saw blade to bend while cutting. For this analysis, it was assumed that the material being cut applied an external load on the circular saw blade. The load was applied at the point where the saw blade first encounters the uncut material. The material was assumed one inch thick, and the saw blade stuck 0.25" above the material. A diagram showing the placement of the external load is shown in Figure 2-1.

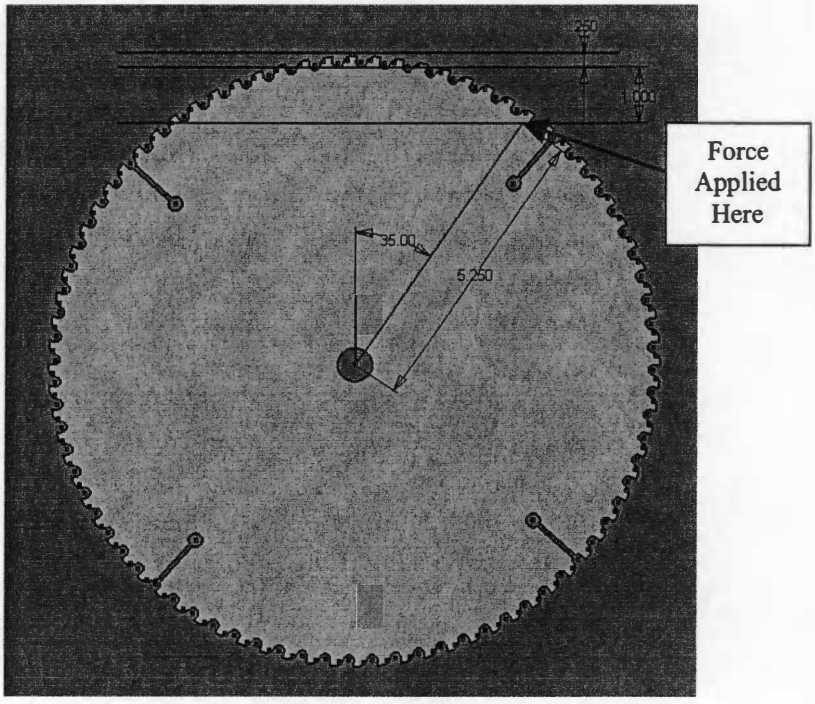


Figure 2-1 Point Where External Load is Applied to Circular Saw Blade Causing it to Bend

2.2 BACKGROUND

Design Space was used to perform the finite element analysis. Design Space is a software package that allows simulations to be run on a 3-D model. Before the simulation is run, an environment must be created. The environment consists of parameters such as how the model is supported, what forces are applied, and what type of solution is wanted from the simulation.

During the finite element analysis for the circular saw blade, one general environment was used throughout. The parameters of the environment and their descriptions are shown in Table 2-1. The only things that changed in the environment were the magnitudes and positions of the applied forces.

2.3 CREATING A CIRCULAR SAW BLADE MODEL

Two saw blade models were created in Inventor. The models were made to represent the saw blade that would be used for testing on the prototype. The general dimensions of the saw blade models are given in Table 2-2.

The two models varied in complexity. Blade01 resembled a circular steel plate with a hole in the middle, while Blade02 looked more like a saw blade and included the expansion slots and teeth. The models are shown in Figure 2-2.

Table 2-1 Design Space Parameters Used for Finite Element Analysis

Parameter	Type	Description
Support	Cylindrical	The support was placed within the center hole of the saw blade. It fixed the saw blade in the radial, tangential, and axial directions.
Force	Distributed	The magnitude of the force was distributed over an area. Circular areas were added to the saw blade model to provide an area to apply the force.
Solution	Total Deformation	The solution produced a color band on the saw blade indicating the areas of deflection due to the applied forces. The maximum deflection was calculated.

Table 2-2 General Dimensions of Circular Saw Blade Models

Parameter	Dimension
Diameter of Body	11"
Thickness of Body	0.052"
Diameter of Arbor	0.625"

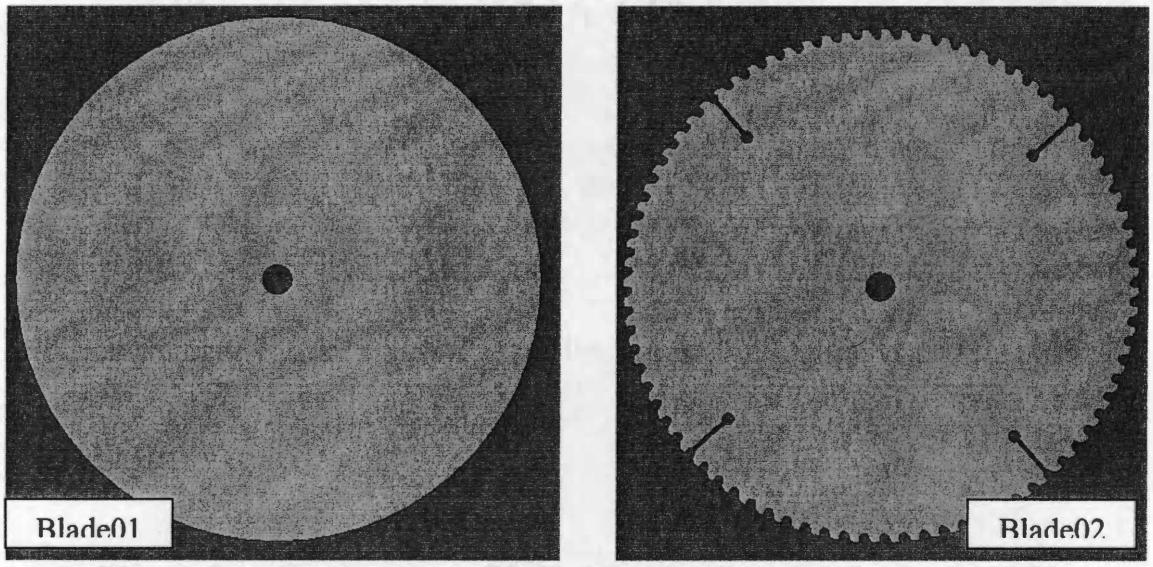


Figure 2-2 Circular Saw Blade Models Used for Finite Element Analysis

2.4 HOW A CIRCULAR SAW BLADE BENDS

A test was performed to examine how a saw blade deflects due to an external force applied at its outer edge. Both saw blade models were tested for comparison.

Experimental

Within Design Space, a single force was applied 5.25" from the arbor of the saw blade model as shown in Figure 2-3. The force was oriented perpendicular to the plane of the saw blade. It was oriented perpendicular to the plane for simplicity.

The maximum deflection of the saw blade was recorded as the magnitude of the force was varied.

Results

The deflection gradient was parallel with the radial line connecting the center of the saw blade model to the point where the force was applied as shown in Figure 2-4. The colors of the bands indicated the different magnitudes of deflection. The maximum deflection always occurred at the outer edge along the radial line where the load was applied. The red arrow was used to indicate where the maximum deflection occurred.

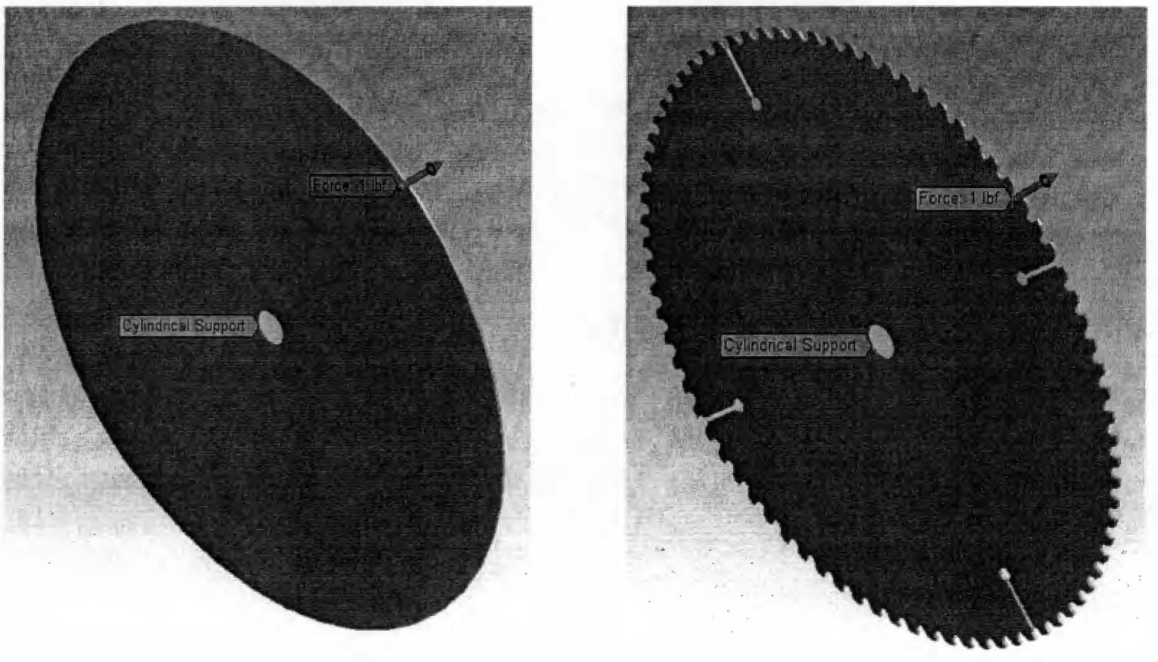


Figure 2-3 Force Applied Perpendicular to the Plane of the Saw Blade Model

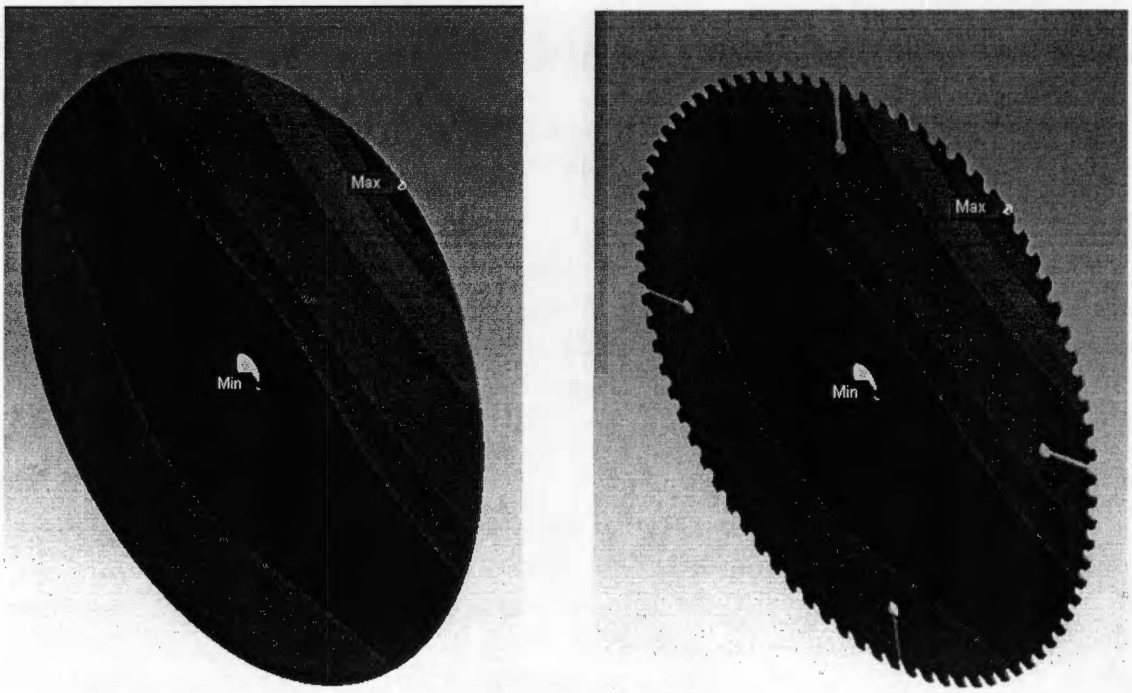


Figure 2-4 Deflection of Saw Blade Model Due to an External Force of 1 lb Applied at the Outer Edge

The maximum deflection versus the magnitude of the force is shown in Figure 2-5. The maximum deflection of Blade02 was consistently greater than that of Blade01. However, the manner in which the saw blades deflected was the same.

Because the simulation time for Blade01 was 80% less than that of Blade02, Blade01 was used for further analysis.

2.5 REDUCING THE DEFLECTION

The results from the deflection tests indicated that the deflection gradient ran parallel with the radial line connecting the arbor and the applied force. Therefore, it was assumed that an external force applied along the line shown in Figure 2-6 could reduce the maximum deflection. A test was performed to determine where the force needed to be applied along this line to reduce the deflection the most.

Experimental

Two forces were applied to Blade01. Force 1 was applied 5.25" away from the arbor of the saw blade model as shown in Figure 2-7. This force was intended to make the saw blade bend. A second force, Force 2, was applied along the radial line shown in Figure 2-6 in the opposite direction. Force 2 was intended to oppose the bending of the saw blade and reduce the deflection. The maximum displacement was recorded as the position of Force 2 on the radial line varied.

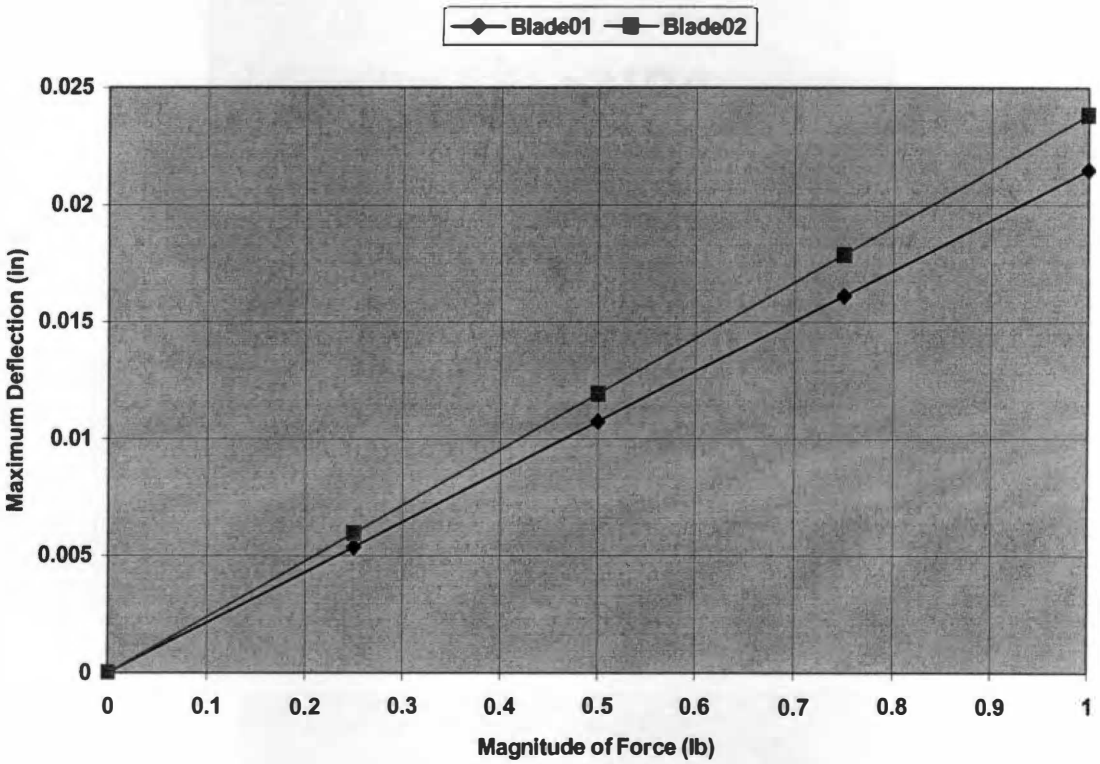


Figure 2-5 Maximum Deflection versus the Magnitude of the Applied Force

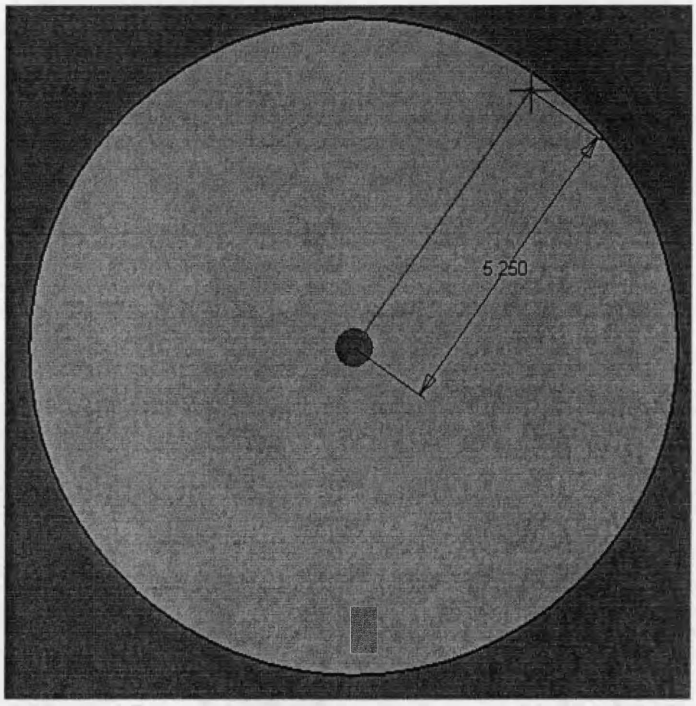


Figure 2-6 Radial Line where Force 2 was Applied to Blade01

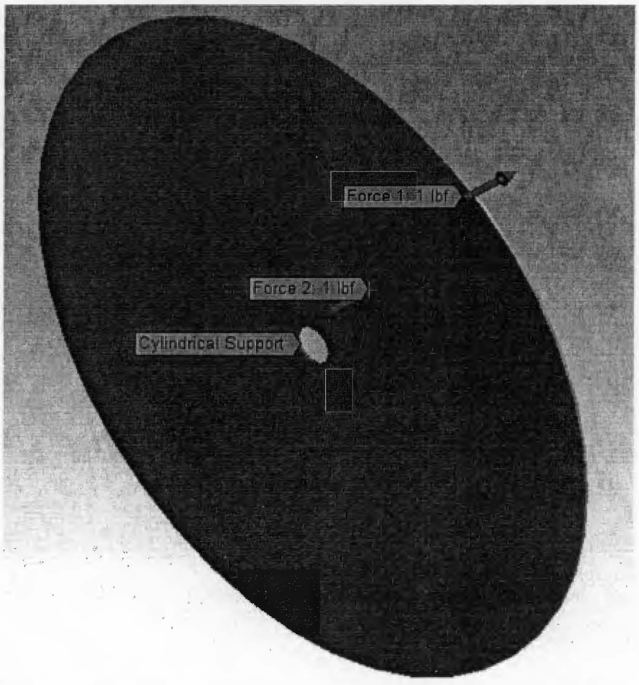


Figure 2-7 Forces Applied to Blade01 to Reduce the Deflection

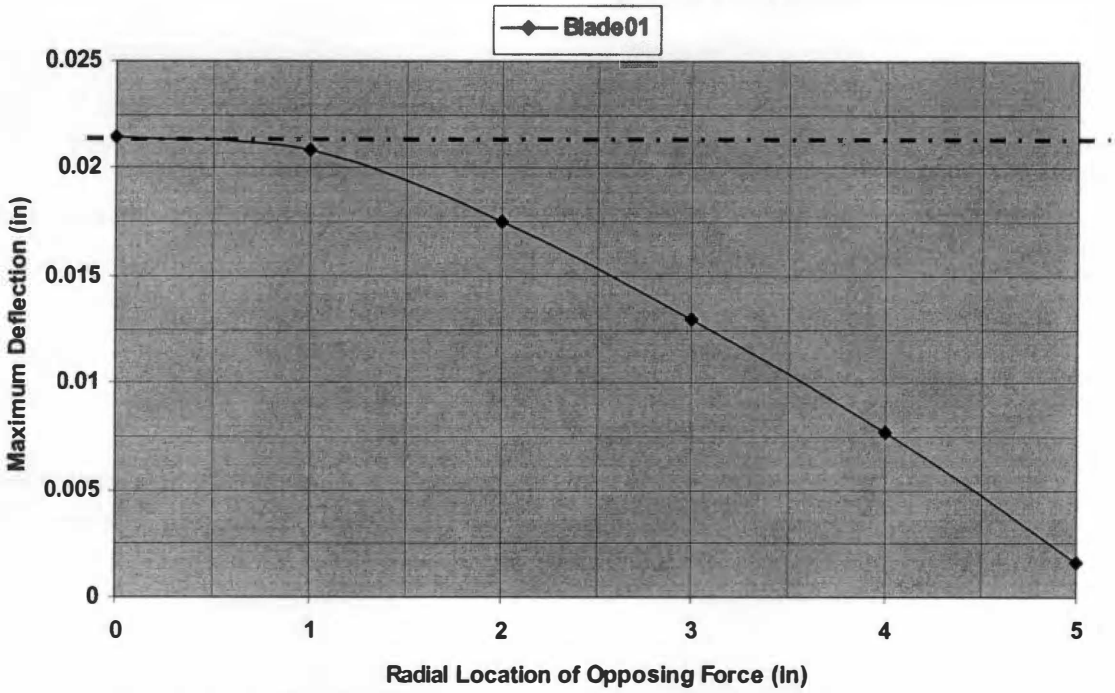


Figure 2-8 Maximum Displacement versus the Radial Distance that the Opposing Force was Applied

Results

The maximum displacement versus the radial distance that Force 2 was applied from the arbor is shown in Figure 2-8. The red dotted line indicates the maximum displacement recorded when there was no opposing force.

As the force was moved out closer to the force causing the bending, the maximum displacement was reduced. For this particular case, the maximum displacement was reduced up to 92%.

2.6 CONCLUSIONS

A circular saw blade bends when an external force is applied perpendicular to its plane at the outer edge. The deflection gradient of the saw blade is parallel to the radial line connecting the center of the saw blade to the point where the external force is applied. If an additional force is applied in the opposite direction along this radial line, then the maximum deflection of the saw blade can be reduced. It is reduced the most when the additional force is near the force causing the bending.

Therefore, on the prototype the electromagnets need to be placed directly under the table of the saw and near the edge of the saw blade where the uncut material first meets the saw blade.

3 System Components

A system is set of components working together to get a desired output. In order to understand how the system will perform, it is necessary to understand how each of the components performs individually.

The following components of the feedback control system were tested to determine their response to various inputs:

- Sensor
- Electromagnets
- Saw blades

Known inputs were applied to the components and their outputs were recorded. The experimental data was used to develop equations that could be used to represent the system components in the mathematical model.

3.1 SENSOR

A proximity transducer system was used within the feedback control system as the sensor to measure the displacement of the saw blade. A test was performed to determine the linear range of the proximity transducer system and its resolution.

Voltage versus Distance

Experimental

The proximity probe was mounted into a piece of angle iron and secured in place. A voltmeter was hooked up to the output of the proximity transducer system to read its output voltage.

Another piece of angle iron was placed directly against the tip of the proximity probe until the output voltage was zero. A caliper was used to measure the distance between the two faces of the angle iron. This distance was recorded as the initial distance.

The caliper was then used to move the angle iron away from the tip of the probe in increments of 0.01" as shown in Figure 3-1. The output voltage of the probe was recorded for each distance. This was repeated until the output voltage no longer changed when the angle iron was moved.

Results

The distance between the tip of the probe and the angle iron was calculated by subtracting the initial distance from the measured distance. The output voltage versus the distance between the angle iron and the tip of the probe is shown in Figure 3-2.

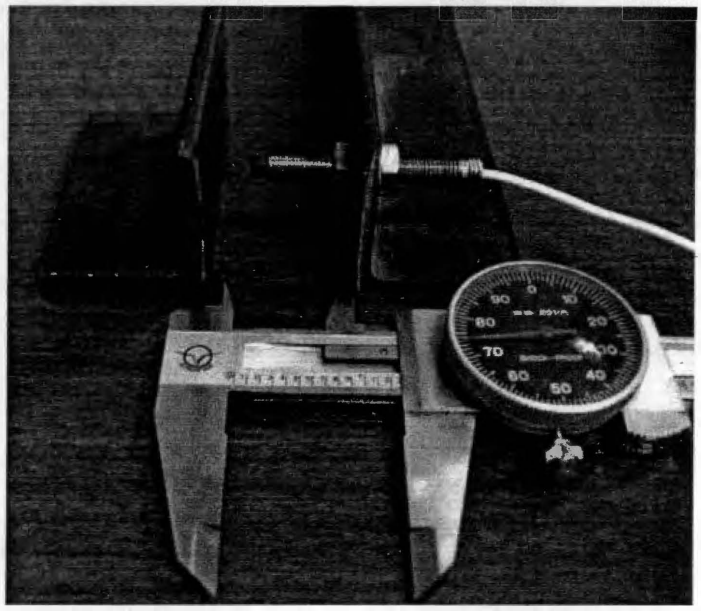


Figure 3-1 Method Used to Determine the Voltage versus Distance Relationship of the Proximity Transducer System

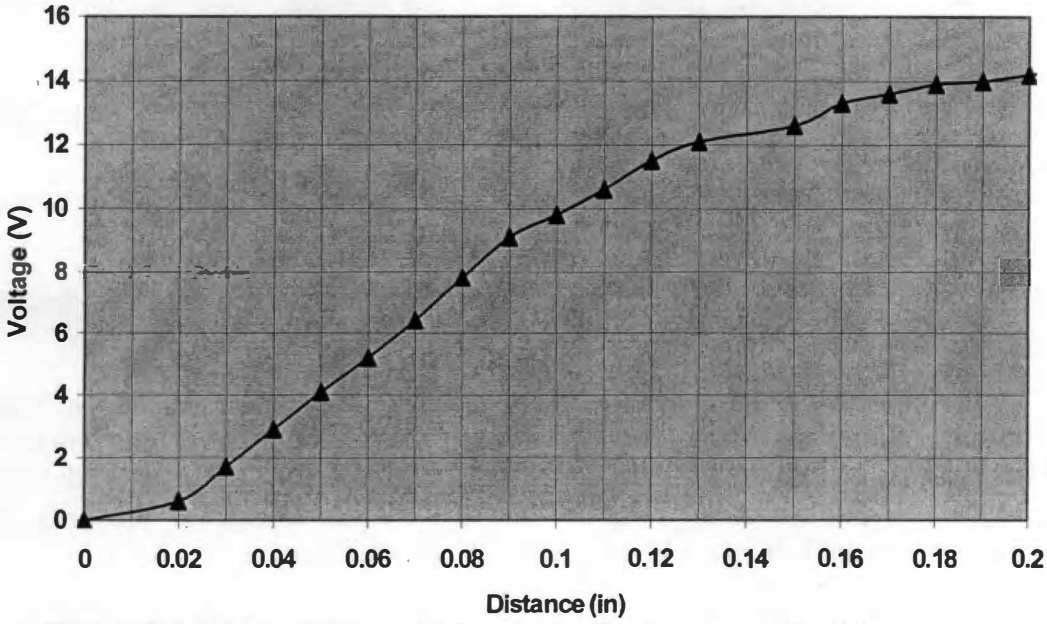


Figure 3-2 Output Voltage of Proximity Probe versus the Distance

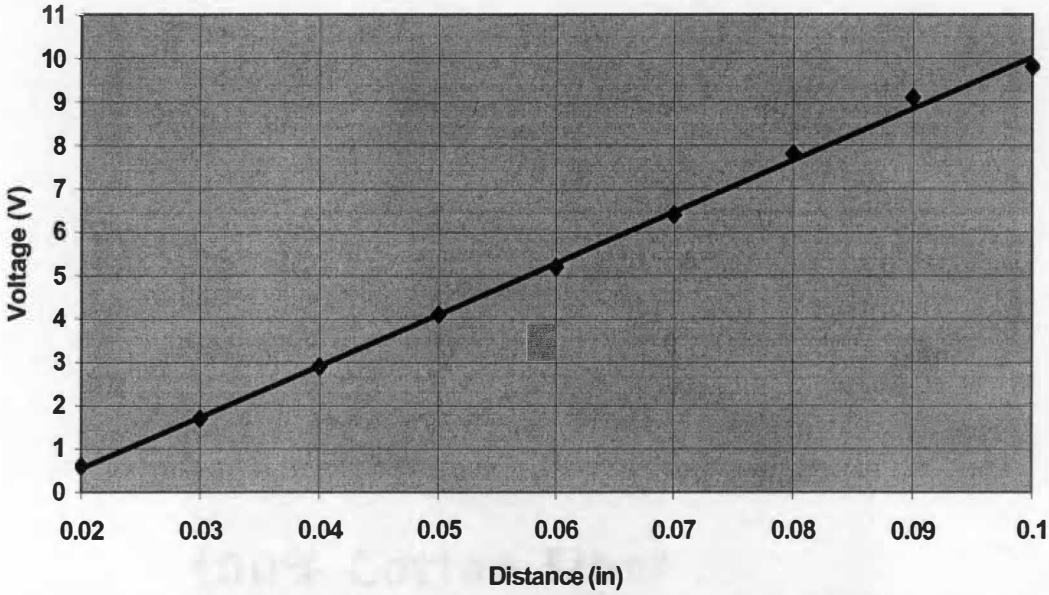


Figure 3-3 Output Voltage of Proximity Probe versus Distance within the Linear Range

The proximity probe could measure the distance between it and a metal object up to 0.20" away. However, the output voltage of the proximity probe versus the distance was only linear over the range of 0.02" – 0.10". A separate graph using the data points within the linear range was created and shown in Figure 3-3.

A linear trend line was fitted to the data points in Excel. Over the linear range, the output voltage as a function of distance was

$$V = 118.5x - 1.821 \qquad \text{Equation (3.1)}$$

where

$x = distance$

The resolution of the proximity probe within the linear range was 118.5 V/in.

Conclusions

In the feedback control system, the proximity probe needs to be positioned approximately 0.06" away from the saw blade. This would allow the proximity transducer system to initially operate at its mid-linear range. The saw blade could displace ±0.04" from its initial position, and the output voltage of the proximity transducer system would change 1 volt every 0.008" of displacement.

3.2 ELECTROMAGNETS

A pair of electromagnets normally used in trailer-brake systems was used in the feedback control system. Before using the electromagnets, tests were performed to determine how much power the electromagnets required, the magnitude of the magnetic force they could provide, and their time constants due to the inductance of the coils.

Power

The electromagnets may be required to run continuously for finite amount of time when used within the feedback control system. The electromagnets heat up when current flows through them due to the resistance R across the electromagnets

$$R = 3.7\Omega$$

If the electromagnets are left on for too long, they could get too hot and fail. A simple test was performed to determine how quickly the temperature of the electromagnets increased over time while continuous power was supplied.

Experimental

A thermocouple was attached to the side of one of the electromagnets. A power supply was used to apply a constant current of 2.5 amps to the electromagnet. The surface temperature of the electromagnet was measured from the thermocouple and recorded in one-minute intervals for 60 minutes. The electromagnet was then disconnected from the power supply and cooled to room temperature.

The electromagnet was then hooked back up to the power supply. This time an aluminum plate was attached to the back of the electromagnet. A constant current of 2.5 amps was supplied to the electromagnet and the surface temperature was measured as before.

Results

The surface temperature of the electromagnet versus time is shown in Figure 3-4. Over time, the surface temperature of the electromagnet increased. The aluminum plate caused the surface temperature to increase at a slower rate. With or without the aluminum plate, the electromagnet handled the power without over heating for a relatively long time considering the application.

Magnetic Force

The magnitude of the magnetic force produced from an electromagnet depends on two things:

1. Amount of current flowing through the electromagnet
2. Distance between the electromagnet and the magnetic material.

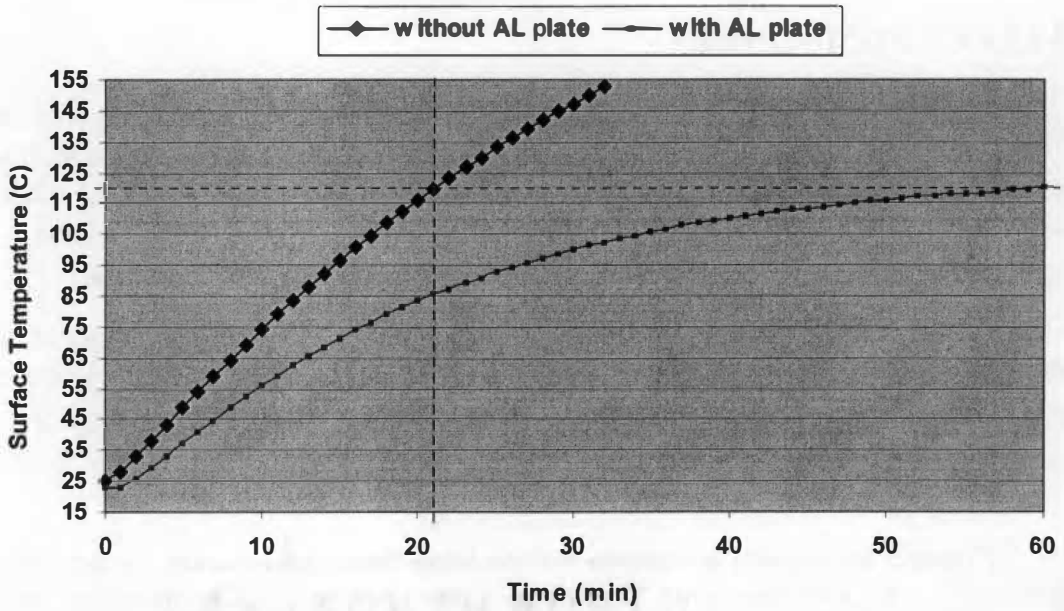


Figure 3-4 Surface Temperature of Electromagnet versus Time with 2.5 Amps

A push-n-slide test was used to measure the magnetic force as the current and distance was changed individually. The results were combined to develop an equation for the magnetic force as a function of current and distance.

Background

The magnetic force produced from an electromagnet can be measured using the push-n-slide test. With this test, the electromagnet is laid on top of a magnetic material. A constant current is then supplied to the electromagnet. A force gauge is used to push on the side of the electromagnet until it begins to slide. If the coefficient of friction between the electromagnet and the surface it's sliding on is known, then the magnitude of the force required to make the electromagnet slide can be used to calculate the magnetic force F_m from

$$F_m = (F / \mu_s) - W \qquad \text{Equation (3.2)}$$

where

F = *force required to cause sliding*
μ_s = *static coefficient of friction.*
W = *weight of the electromagnet*

Experimental

Static Coefficient of Friction Test. The static coefficient of friction μ_s between the electromagnet and a layer of brass shim was determined experimentally. It was necessary to know μ_s to calculate the magnetic force from the push-n-slide test.

The electromagnet was placed on top of a piece of brass shim. They were laid horizontally on a table. A force gauge was used to measure the force required to make the electromagnet slide across the brass shim. The coefficient of friction μ_s was calculated using

$$\mu_s = F / W \qquad \text{Equation (3.3)}$$

where

F = *force required to cause sliding*
W = *weight of the electromagnet.*

The coefficient of friction between the electromagnet and the brass shim was

$$\mu_s = 0.24$$

Push-N-Slide Test. A 0.002" layer of brass shim was placed on top of a 0.125" thick steel plate. The brass shim was attached to the steel plate and secured in place on a table. An electromagnet was laid on top of the brass shim and hooked up to a power supply.

A specific current was supplied to the electromagnet from the power supply. The magnetic force created by the current made the electromagnet and steel plate attract to one another. A digital force gauge was used to push perpendicularly on the side of the electromagnet as shown in Figure 3-5. The magnitude of the force required to make the electromagnet slide was measured and recorded.

Additional layers of brass shim, each having a thickness of 0.002", were then placed between the steel plate and the electromagnet. As each layer was added, the force required to make the electromagnet slide at various current levels was recorded.

The magnetic force F_m produced from the electromagnet at the different distances and currents was calculated using

$$F_m = (F / \mu_s) - W \qquad \text{Equation (3.4)}$$

where

F = *force required to cause sliding*
μ_s = *static coefficient of friction.*
W = *weight of the electromagnet*

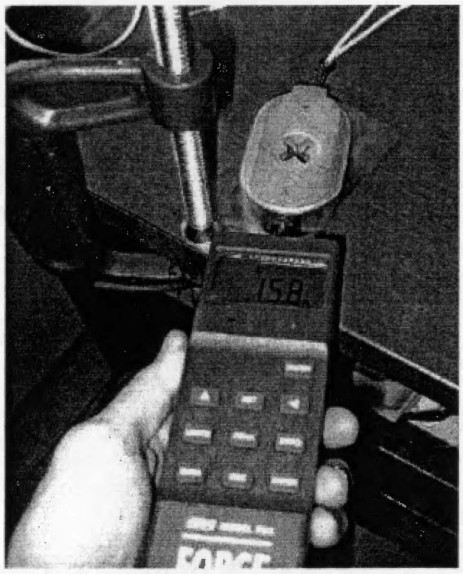


Figure 3-5 Test Used to Measure the Magnetic Force Produced from the Electromagnets

Results

The magnitude of the magnetic force as a function of distance and current is shown in Figure 3-6. Exponential trend lines were fitted to the data points produced from each current level. The general form of the equations representing the fitted lines was

$$F_m = C_i * e^{(-r_i * x)} \qquad \text{Equation (3.5)}$$

where

C_i = *function of current*

r_i = *function of current*

i = *current*

x = *distance*

Table 3-1 shows the values C_i and r_i for each current level. The values for C_i and r_i versus the current were plotted. The objective was to determine how C and r were dependent on the current. The graphs are shown in Figure 3-7 and Figure 3-8 respectively.

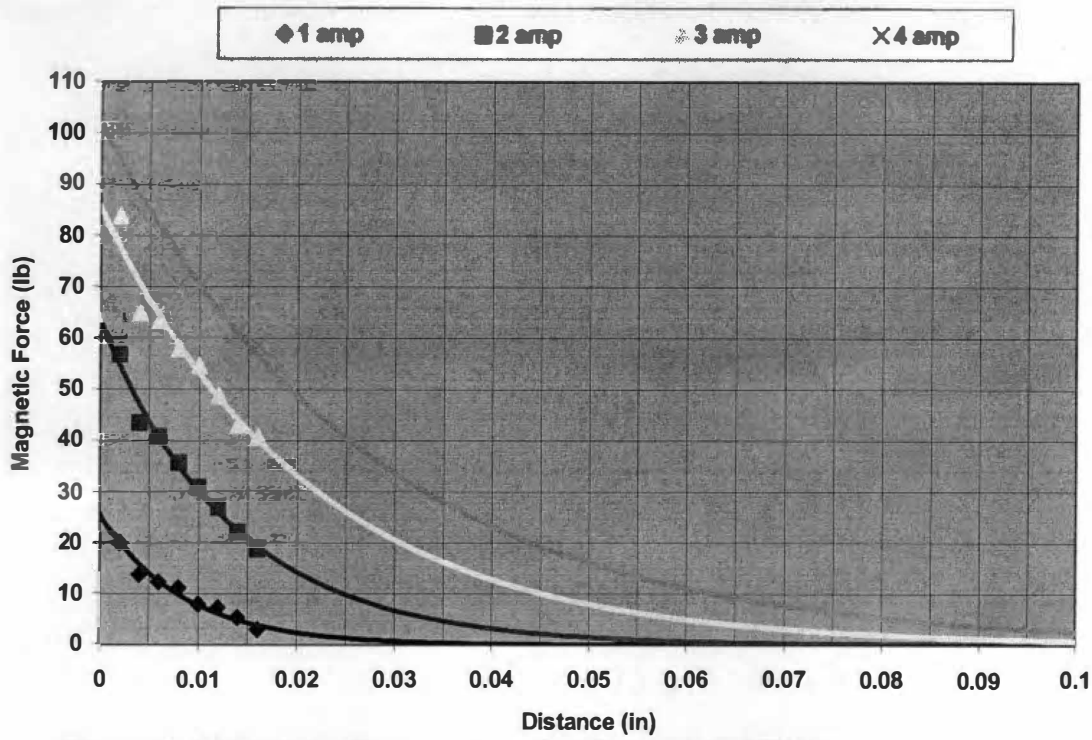


Figure 3-6 Magnetic Force versus the Current and Distance

Table 3-1 Experimental Values of C_i and r_i in the Magnetic Force Equation

Current (amps)	C_i	r_i
1	25.437	118.9
2	63.493	74.652
3	85.393	47.495
4	102.12	36.989

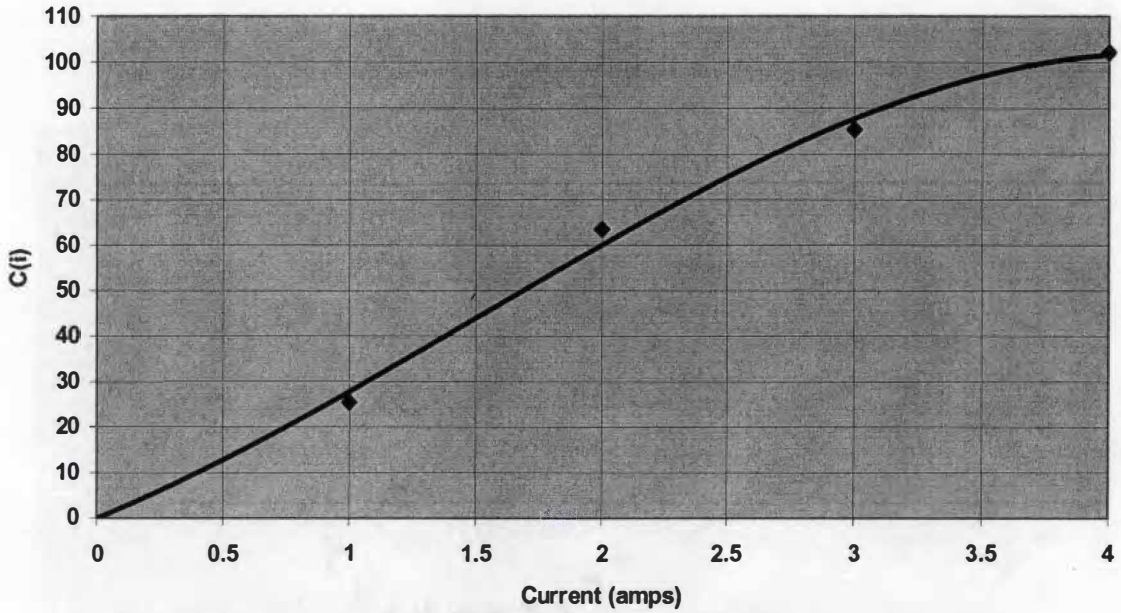


Figure 3-7 The Function C(i) in the Magnetic Force Equation

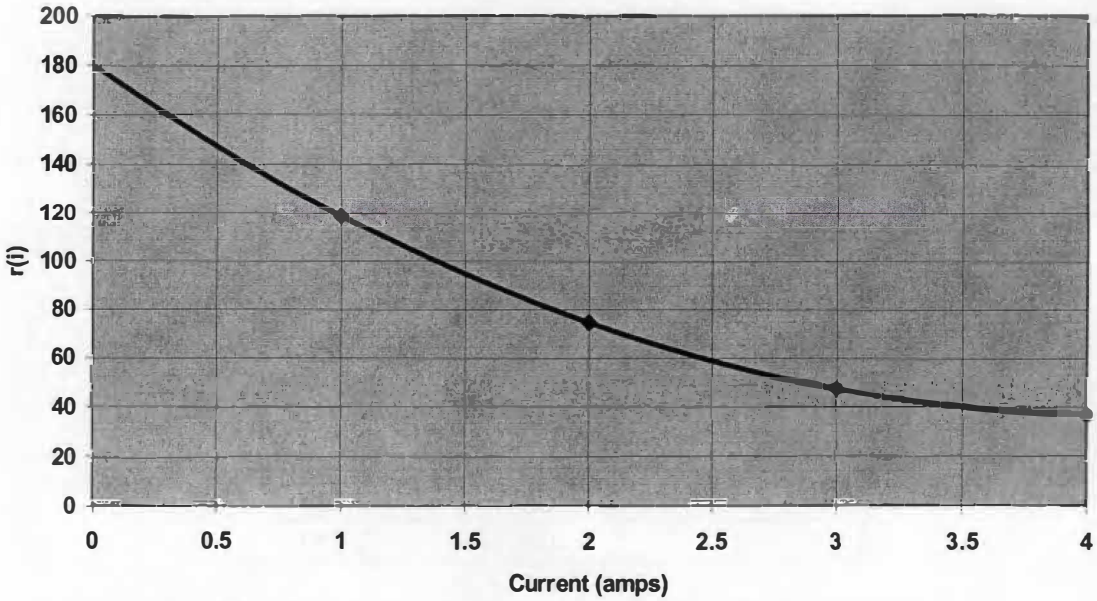


Figure 3-8 The Function r(i) in the Magnetic Force Equation

A 3rd order polynomial was used to provide a best fit trend line for the C(i) data points. In order to make the magnetic force equal to zero when there was no current, the y-intercept of the trend line was forced to equal zero. This allowed C(0) = 0 when the current was zero. The equation giving the function C(i) within the current range of 0-4 amps was

$$C_i = -1.5307 * i^3 + 6.8681 * i^2 + 22.404 * i \qquad \text{Equation (3.6)}$$

where

i = *current.*

A 2nd order polynomial was used to provide a best fit trend line for the r(i) data points. The equation giving the function r(i) within the current range of 0-4 amps was

$$r_i = 5.624 * i^2 - 46.313 * i + 119.94 \qquad \text{Equation (3.7)}$$

where

i = *current.*

Time Constant

Due to inductance, the magnetic force produced from an electromagnet cannot be turned on and off instantaneously. It takes a small amount of time for the current flowing through the electromagnet to change from its initial value to its final value. This time delay limits the frequency response of the feedback control system.

A test was performed to determine the time required for current flowing through the electromagnet to go from 0% to 62.3% of its final value.

Experimental

The circuit shown in Figure 3-9 was created to help determine the time constant of the electromagnet. Resistor R1 represents the resistance across the electromagnet, and R2 represents an external resistance added for the experiment. The resistance of R2 was 92% less than R1.

A signal generator was used to remotely supply a step input voltage to the circuit through the power supply. The rise-time function on the oscilloscope was used to measure the time required for the voltage across R2 to go from 10% to 90% of its final value. The data was then used in Simulink to get an approximation of the time required for the voltage to go from 0% to 62.3%.

The model as shown in Figure 3-10 was created to represent the output voltage across resistor R2. The variable *tau* in the transfer function represents the time constant. A step input was applied to the model and the output voltage versus time was plotted.

A step input was applied to the model with various values for *tau*. When the simulated output voltage was the same as that measured from the oscilloscope, then that particular value of *tau* was considered the time constant of the electromagnet.

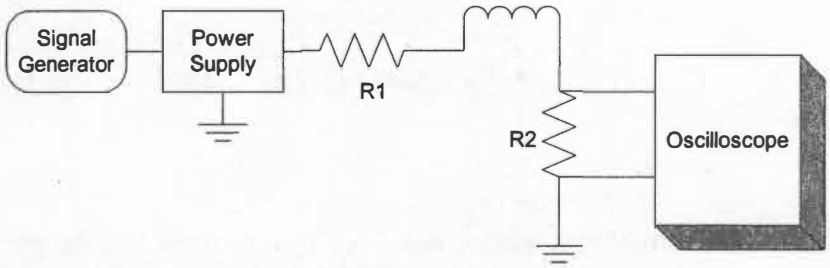


Figure 3-9 Circuit Used to Determine Time Constant of Electromagnet

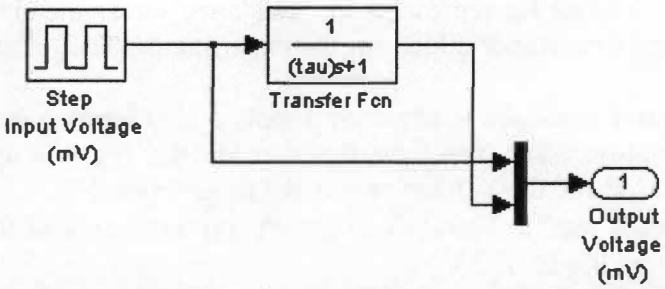


Figure 3-10 Model Used to Determine Time Constant of Electromagnet

Results

The measured voltage across resistor R2 went from zero to 236 mV. The rise-time was measured to be 0.006 milliseconds.

Using the Simulink model, the value of *tau* was fixed to give the voltage versus time as shown in Figure 3-11. The value of *tau* that gave these results was

$$tau = 0.002\text{sec.}$$

Conclusions

A power supply that could put out at least four amps would be needed to power the electromagnets in the feedback control system. The electromagnets draw approximately 60 watts of power when 4 amps is going through them.

The magnetic force F_m produced from the electromagnets can be approximated by

$$F_m = C_i * e^{(-r_i * x)} \qquad \text{Equation (3.8)}$$

where

$$C_i = -1.5307 * i^3 + 6.8681 * i^2 + 22.404 * i \qquad \text{Equation (3.9)}$$

$$r_i = 5.624 * i^2 - 46.313 * i + 119.94 \qquad \text{Equation (3.10)}$$

and

$i = current$
$x = distance$

If the electromagnets were initially placed 0.05" from the saw blade in the feedback control system, they could still provide up to approximately 15 lbs. of force with 4 amps.

The time constant of the electromagnets will limit the frequency response of the entire feedback control system. The time constant of the electromagnet was 0.002 seconds.

3.3 SAW BLADES

Two relatively thin circular saw blades were fabricated to use in testing the feedback control system. The bodies of the saw blades were 0.052" and 0.065" thick each having an 11" outer diameter. A normal circular saw blade with the same diameter is approximately 0.125" thick.

Before using the circular saw blades, tests were conducted to determine the saw blades natural frequencies and their equivalent stiffness at the outer edge.

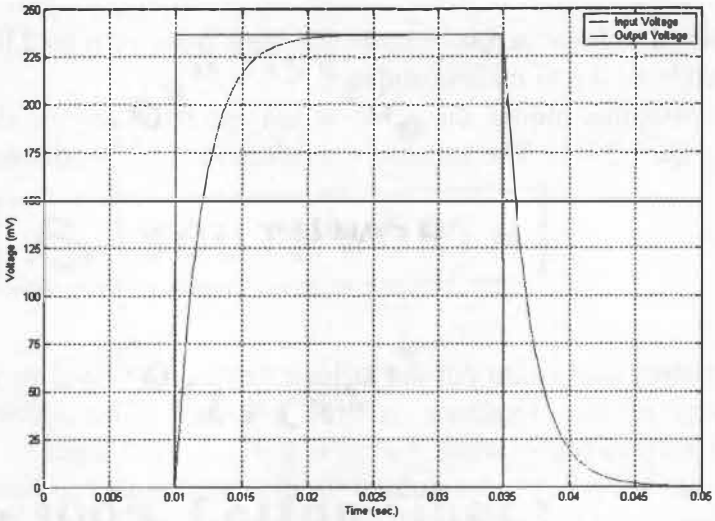


Figure 3-11 Simulated Voltage across Resistor R2 versus Time

Test Jig

The jig shown in Figure 3-12 was created to hold the saw blades throughout the experimental tests. The saw blades were mounted horizontally on the shaft of the jig. A set of washers and nuts were used to tighten the saw blades in place on the shaft. The diameters of the washers were approximately the same size as the collars that would be used on the prototype saw.

An additional fixture was made to mount the proximity probe above the outer edge of the saw blades. The proximity probe was used to measure the displacement of the saw blade in the stiffness test.

Natural Frequency

Circular saw blades want tend to vibrate at certain frequencies when impulses are applied to them. The values of the frequencies depend on the geometry of the saw blades and how they are supported. A test was performed to determine the natural frequencies for the two circular saw blades.

Experimental

A circular saw blade was mounted onto the test jig. A microphone was placed near the saw blade and hooked into the sound card of a computer. The edge of the saw blade was displaced about 0.05", and then released. This caused the saw blade to begin vibrating.

The sound waves created from the vibrating saw blade were sampled at a rate of 11025 Hz. The computer program, FFTSCOPE 1.2, collected the input data. The Fast Fourier Transform (FFT) of the data was taken to determine the frequency content of the sound waves.

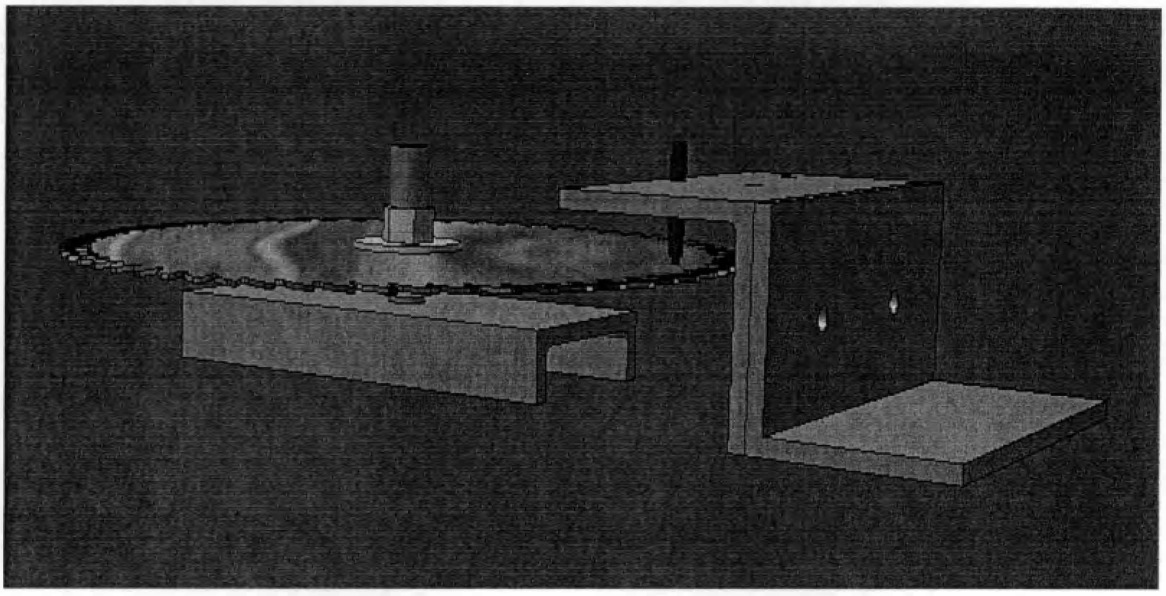


Figure 3-12 Jig Used for Holding Saw Blade throughout Natural Frequency and Stiffness Test

Results

The FFT results for the 0.052" and 0.065" circular saw blades are shown in Figure 3-13 and Figure 3-14 respectively. Frequencies higher than 750 Hz were not included on the graphs in order to improve the resolution at low frequencies. Frequencies in the FFT plots that had significantly larger magnitudes were considered the natural frequencies of the saw blades. Table 3-2 shows the lowest natural frequencies estimated from the FFT plots.

Equivalent Stiffness

The stiffness of the circular saw blades was needed in order to represent the saw blades as a spring-mass-damper system in a mathematical model. The equivalent stiffness was determined at the outer edge of the saw blades because that is where the electromagnets were going to apply a magnetic force.

Experimental

A saw blade was mounted onto the test jig. The proximity probe previously tested was mounted above the outer edge of the saw blade. The face of the probe was positioned below one of the gullets (gap between saw blade teeth). The initial distance between the probe and saw blade was set insure the probe stayed within its linear range throughout the experiment. The initial output voltage V_0 of the probe was recorded.

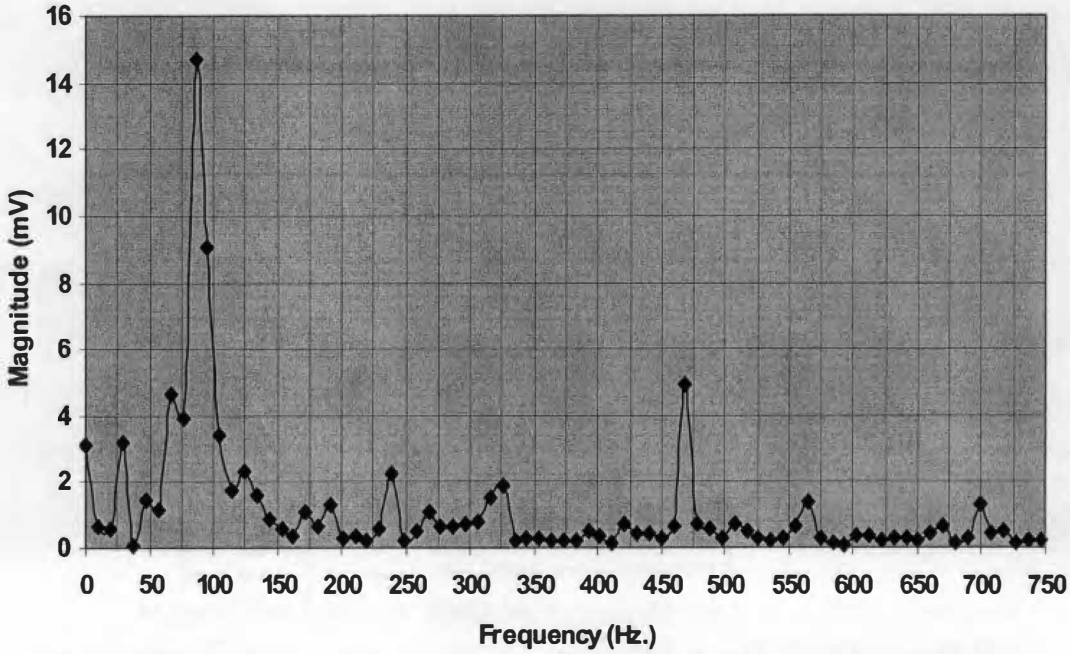


Figure 3-13 Frequency Content of 0.052" Thick Circular Saw Blade

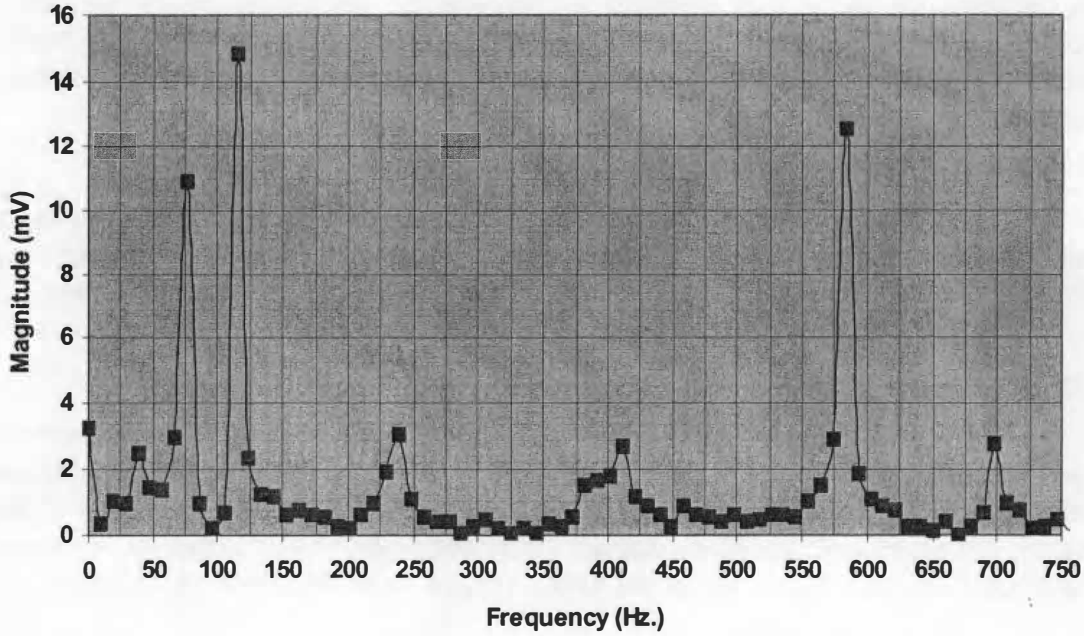


Figure 3-14 Frequency Content of 0.065" Thick Circular Saw Blade

Table 3-2 Saw Blades Lowest Natural Frequencies

Saw Blade Thickness (in)	Lowest Natural Frequency (Hz)
0.052"	70
0.065"	77

A paper clip was then used to hang a weight from one of the saw blades teeth. The weight was hung directly below the probe and near the bottom of the tooth's gullet as shown in Figure 3-15. The weight caused the saw blade to bend, and the output voltage of the probe changed due to the deflection. The new output voltage and the amount of weight were recorded.

This same procedure was repeated using different amounts of weight. The output voltage was recorded each time.

Results

The linear relationship between the distance x and the output voltage V of the proximity probe

$$x = 0.0084 * V + 0.0154 \qquad \text{Equation (3.11)}$$

was used to calculate the displacement X of the saw blade for each different weight

$$X = 0.0084 * (V - V_0) \qquad \text{Equation (3.12)}$$

where

V = measured output voltage with weight
V_0 = initial output voltage without weight

The force from the weight versus the displacement for the 0.052" and 0.065" saw blades is shown in and Figure 3-16. Linear trend lines were fitted to the data points. The equivalent stiffness of the saw blades was determined from the slopes of the lines.

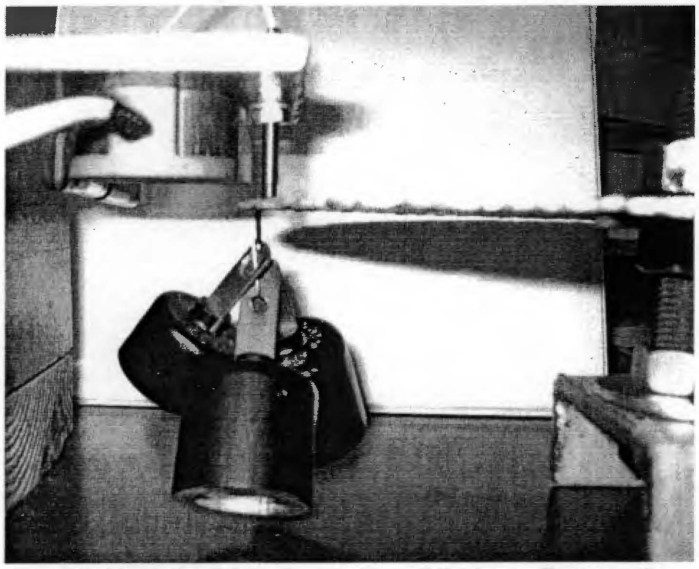


Figure 3-15 Weights Hanging from Saw Blade to Determine Equivalent Stiffness

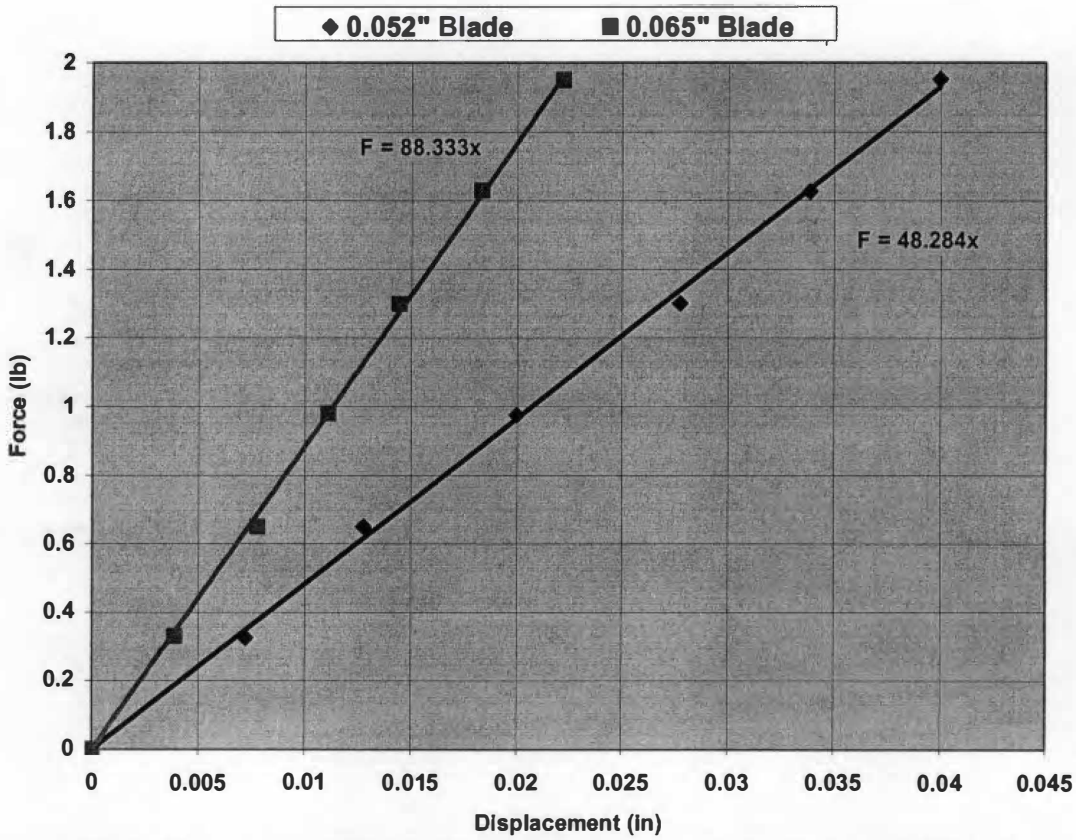


Figure 3-16 Force versus the Displacement of the Circular Saw Blades

Conclusions

The lowest natural frequencies of the saw blades were around 70 to 80 Hz. The rate at which the electromagnets are being turn on and off will need to be significantly less than 70 Hz. in order to keep from excited the saw blades. The equivalent stiffness of the saw blades is shown in Table 3-3.

As an example, consider that the 0.052" saw blade was displaced 0.02" while cutting. This could be the result of a 1.0 lb applied perpendicular to the side of the saw blade from the material being cut. Previous test showed that the electromagnets could provide a sufficient amount of force to the saw blade to bring it back into its initial position. This indicates that the electromagnets can produce enough force to increase the lateral stiffness of the circular saw blades.

Table 3-3 Equivalent Stiffness of Circular Saw Blades

Saw Blade Thickness (in)	Equivalent Stiffness (lb/in)
0.052"	48.3
0.065"	88.3

4 Mathematical Model

A mathematical was developed in Simulink to help understand the dynamics of the feed back control system shown in Figure 4-1.

It was assumed that the electromagnets and the proximity probe were placed at the outer edge of the saw blade. The initial distance between the electromagnets and the saw blade was *a* and the initial distance between the proximity probe and the saw blade was *b*. The displacement *x* of the saw blade was defined to be *(+)* if displaced to the right, and *(-)* if displaced to the left.

In order to create the mathematical model, sub-systems were created to represent each component of the feedback control system. The sub-systems were tested individually to ensure they worked properly. They were then combined to form a complete model.

Throughout the following sections, the development of each sub-system is discussed. In conclusion, the sub-systems are combined to form a complete mathematical model.

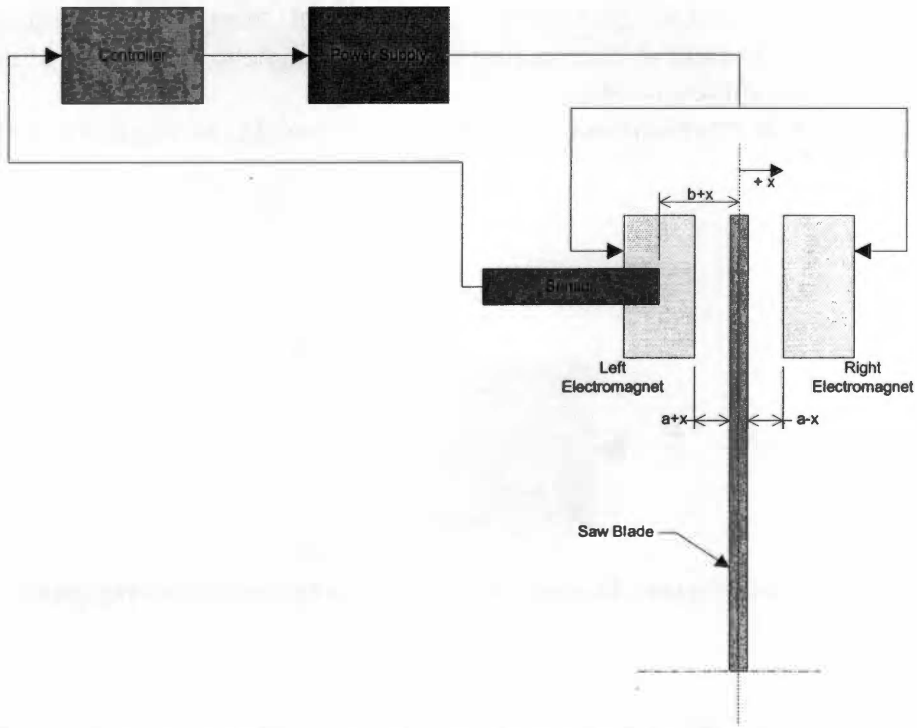


Figure 4-1 Feedback Control System Modeled in Simulink

4.1 SAW BLADE

The saw blade was represented as a spring-mass-damper system as shown in Figure 4-2. The equivalent mass m was defined as

$$m = k / w_n \qquad \text{Equation (4.1)}$$

where

k = *equivalent stiffness of saw blade*
w_n = *lowest natural frequency of saw blade.*

The force F represented the summation of the external forces applied on the saw blade at the outer edge.

The mathematical model shown in Figure 4-3 was used to represent the saw blade in the feedback control system.

The input to the model was an external force F. The external force was added to the spring force and the damping force of the system. The sum of the forces was multiplied by the equivalent mass and the integral of the acceleration was taken twice to get the displacement. The displacement was converted from feet to inches. The saturation block was used to prevent the displacement from exceeding $\pm a$. This prevented the saw blade from deflecting past the electromagnets. The output of the model was the displacement of the saw blade.

The sub-system representation of the saw blade model is shown in Figure 4-4.

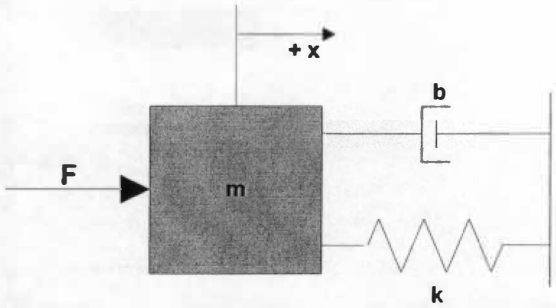


Figure 4-2 Spring-Mass-Damper System Used to Represent the Saw Blade

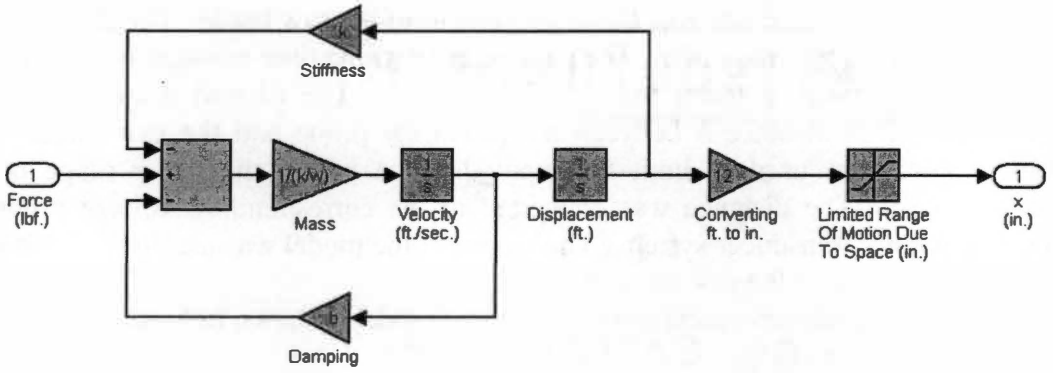


Figure 4-3 Mathematical Model of the Saw Blade

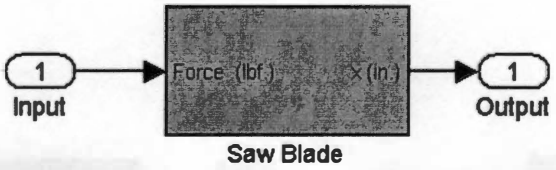


Figure 4-4 Sub-System Used to Represent the Saw Blade Model

4.2 SENSOR

The mathematical model shown in Figure 4-5 was used to represent the sensor in the feedback control system.

The input to the sensor was the displacement of the saw blade. The displacement was taken through a low-pass filter. The parameter *t* was the time constant of the filter. It could be used to raise or lower the cutoff frequency. The filtered displacement was added to the initial distance *b* between the proximity probe and the saw blade. The saturation block was used to limit the input distance within the linear range of the proximity probe. The distance was converted to the corresponding voltage produced from the proximity transducer system. The output of the model was the distance between the proximity probe and the saw blade in volts.

The sub-system representation of the sensor model is shown in Figure 4-6.

4.3 CONTROLLER

The control method used for the feedback control system was proportional control. The mathematical model shown in Figure 4-7 was used to represent the proportional controller in the feed back control system.

The input to the model was the distance between the saw blade and the proximity probe in volts. The input was subtracted from the initial distance *b* between the proximity probe and the saw blade. Note that the value of *b* was initially in inches and then converted to volts using the voltage versus distance equation from the proximity transducer system. The difference between *b* and the input distance was multiplied by the proportional gain k_p. The output of the model was the control voltage.

The sub-system representation of the proportional controller is shown in Figure 4-8.

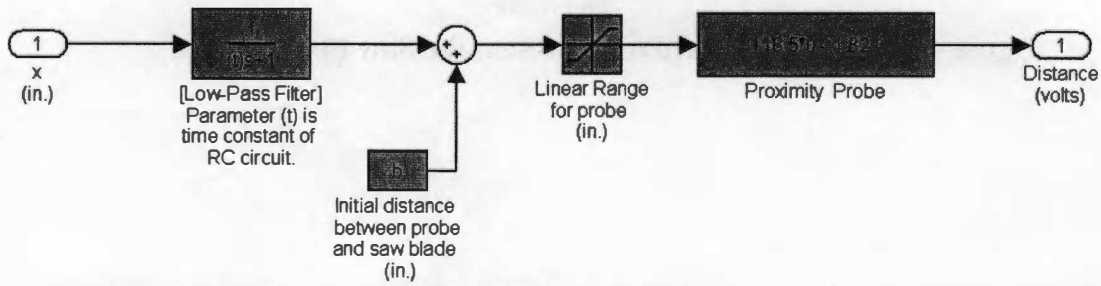


Figure 4-5 Mathematical Model of the Sensor

Figure 4-6 Sub-system Used to Represent the Sensor

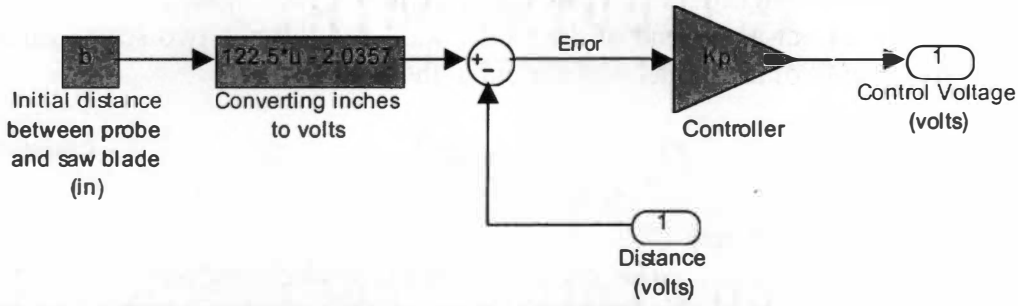


Figure 4-7 Mathematical Model of Proportional Controller

Figure 4-8 Sub-System Used to Represent the Proportional Controller

4.4 POWER SUPPLY

The mathematical model shown in Figure 4-9 was used to represent the power supply in the feedback control system.

The input to the model was the control voltage in volts. The control voltage was multiplied by the inverse of the resistance of the RL circuit. The voltage was converted from volts to amps. Switches were used to determine which electromagnet would receive current.

If the current was a *(-)* value, then the top switch allowed the current to pass through and the bottom switch outputted the constant zero. Likewise, if the current was a *(+)* value, then the bottom switch allowed the current to pass through and the top switch outputted the constant zero.

Because the top switch allowed *(-)* values to pass through, the absolute value of the output was taken in order to prepare the value for the next model.

The black bar at the end of the model was used join the two scalar values into a vector. The output of the model was current in the vector form

$$\bar{u} = [u1, u2] \qquad \text{Equation (4.2)}$$

where

u1 = current going to left-electromagnet
u2 = current going to right-electromagnet

The sub-system representation of the power supply is shown in Figure 4-10.

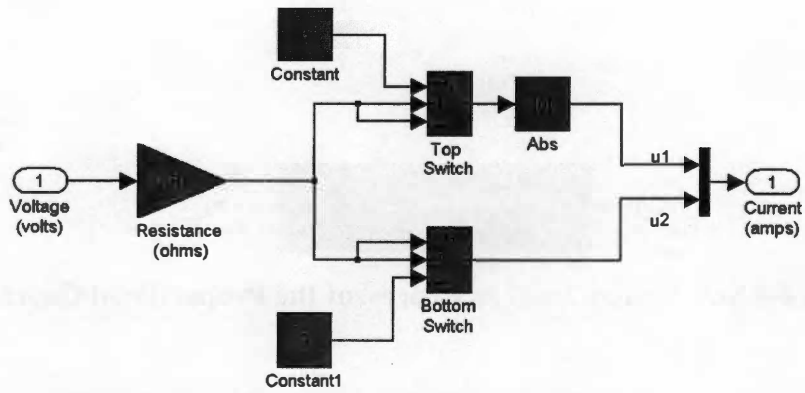


Figure 4-9 Mathematical Model of the Power Supply

Figure 4-10 Sub-System Used to Represent the Power Supply

4.5 ELECTROMAGNETS

The mathematical model shown in Figure 4-11 was used to represent an electromagnet in the feedback control system.

The input to the model was current. A first order transfer function was used to account for the inductance of the electromagnet. The parameter *tau* denoted the time constant. The current was put into two functions to determine the constants *C* and *r*. The distance between the electromagnet and the saw blade along with the *C* and r values were inputted to magnetic force equation

$$F_m = C_i * e^{(-r_i * x)} \qquad \text{Equation (4.3)}$$

where

i = current

x = distance between electromagnet and saw blade

The output of the model was the magnetic force produced from the electromagnet with the specific current and distance input.

The sub-system representation of the electromagnet is shown in Figure 4-12.
The mathematical model shown in Figure 4-13 was used to represent both electromagnets in the feedback control system.

The input to the model was current in vector form *[u1, u2]*. The component *u1* went to the left-electromagnet and the component *u2* went to the right-electromagnet. The initial distance *a* between the electromagnets and the saw blade was added to the displacement *x* of the saw blade. The total distance in was inputted to the electromagnet sub-systems. The output of the sub-systems was the magnetic force. The output of the model was the summation of the magnetic forces from both electromagnets.

The sub-system representation of the model representing both electromagnets is shown in Figure 4-14.

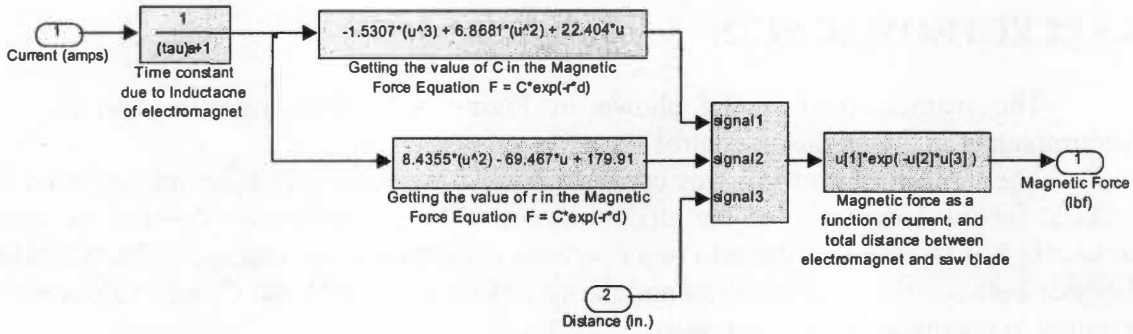


Figure 4-11 Mathematical Model of One Electromagnet

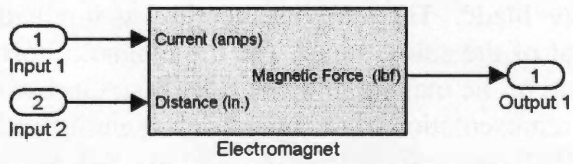


Figure 4-12 Sub-System Used to Represent One Electromagnet

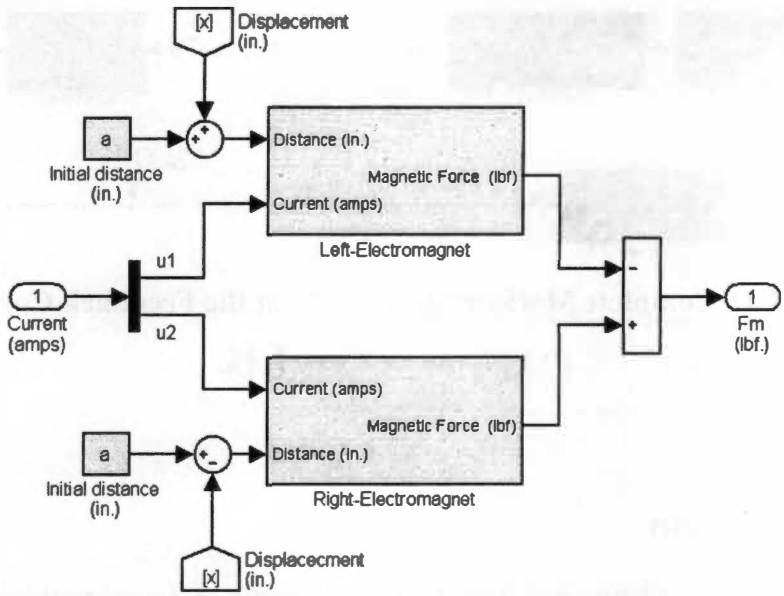


Figure 4-13 Mathematical Model Used to Represent Two Electromagnets

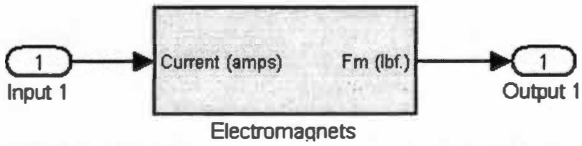


Figure 4-14 Sub-System Representation of Both Electromagnets

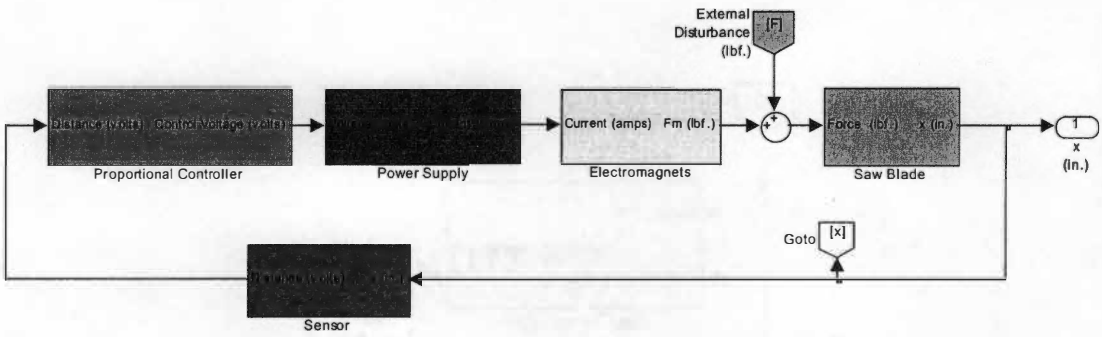


Figure 4-15 Complete Mathematical Model of the Feedback Control System

4.6 CONCLUSIONS

The complete mathematical model with all the sub-systems combined is shown in Figure 4-15.

The input to the model was an external disturbance applied to the saw blade. The sensor measured the displacement of the saw blade and supplied an input voltage to the proportional controller. The controller determined the error of the position versus some reference value and created a control voltage that was proportional. The power supply converted the control voltage into current and supplied the electromagnets with amps. The electromagnets produced a magnetic force in effort to reduce the displacement to zero. The output of the mathematical model was the displacement of the saw blade.

Note that the Go To block was used to link the actual displacement of the saw blade to each electromagnet sub-system.

5 Testing of Mathematical Model

The mathematical model shown in Figure 5-1 was used to test the response of the feedback control system to various inputs. A ramped input was used to test the stiffness of the saw blade, and a step input was used to test the dynamic response of the system.

The following sections discuss the parameters that were used in the mathematical model and the responses to the ramped and step input.

5.1 PARAMETERS

The feedback control system had two adjustments:

1. Proportional gain *Kp*
2. Time constant *t* of low-pass filter.

Throughout the testing of the mathematical model, these only two parameters were changed. The other parameters shown in Table 5-1 remained the same.

The initial distance between the electromagnets and the saw blade was assumed 0.05". They were placed as close as possible to the saw blade so they could provide enough force. However, they needed to be far enough away from the saw blade to prevent the saw blade from deflecting into them.

The initial distance between the proximity probe and the saw blade was assumed 0.06". The saw blade could deflect ± 0.04" and still be within the linear range of the probe.

The damping factor ζ was assumed 0.10. It was not determined experimentally because it varies depending on the material that is being cut. However, a relatively low value was chosen because the saw blade vibrates when cutting.

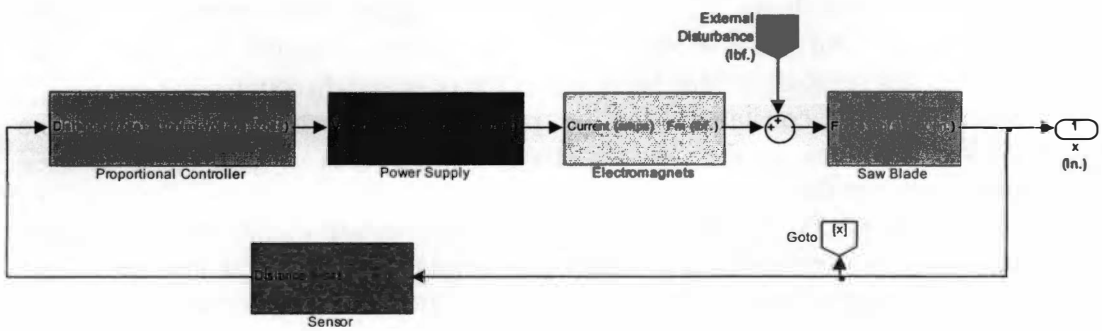


Figure 5-1 Mathematical Model of the Feedback Control System

Table 5-1 Parameters Used for Testing of Mathematical Model

Parameter	Description
$k = 580$	Equivalent stiffness of saw blade at the outer edge (lb / ft)
$w = 440$	Lowest natural frequency of saw blade (rad / sec)
$m = k / w$	Equivalent mass of the saw blade at the outer edge (lb)
$\zeta = 0.10$	Damping factor of saw blade
$b = 2 * \zeta * w * m$	Damping coefficient of saw blade (lb / sec)
$tau = 0.002$	Time constant of electromagnet (sec)
$R = 3.7$	Equivalent resistance of electromagnet circuit (ohm)
a = 0.05	Initial distance between electromagnets and saw blade (in)
b = 0.06	Initial distance between proximity probe and saw blade (in)

5.2 RAMPED INPUT

A ramped input (force linearly increased from zero to 2 lb in eight seconds) was applied to the mathematical model as an external disturbance. The proportional gain *Kp* and the time constant *t* of the low-pass filter were varied to determine how they affected the feedback control system in increasing the stiffness.

The magnitude of the ramped force versus the displacement with *Kp* and *t* equal to zero (control system off) was plotted to use as a reference. It is shown in Figure 5-2.

The magnitude of the ramped force versus the displacement of the saw blade with *Kp* and *t* not equal to zero (control system on) is shown in Figure 5-3.

As *Kp* was increased, the stiffness increased. However, the system became unstable if the gain was too high. The dark areas on the graphs were produced from the saw blade oscillating. Only half of the oscillation is shown because the scale of the horizontal axis was not set to show displacement in the negative direction.

Increasing the time constant of the low-pass filter increased the stability of the system. With higher values for the time constant, higher values of gain could be used without the saw blade oscillating.

The instability of the system was due to the inductance of the electromagnets. The electromagnets could not respond quick enough to the input. The low-pass filter helped in limiting the high frequencies, however, it slowed down the frequency response of the entire system.

A simple test was performed to determine what the response of the system would be like if the electromagnets had a time constant of zero. A ramped input was applied to the feedback control system with various values of *Kp*. The stiffness of the saw blade is shown in Figure 5-4.

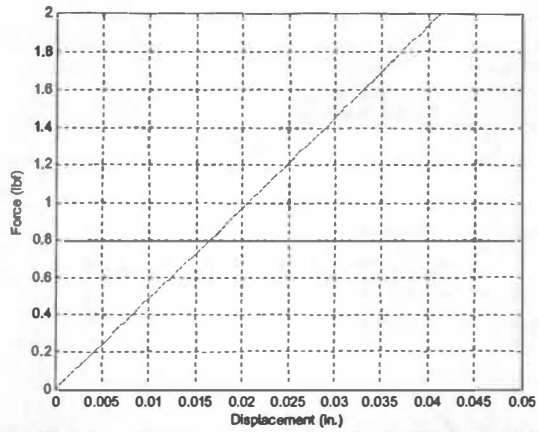


Figure 5-2 Force versus Displacement of 0.052" Saw Blade with Kp and t Equal to Zero

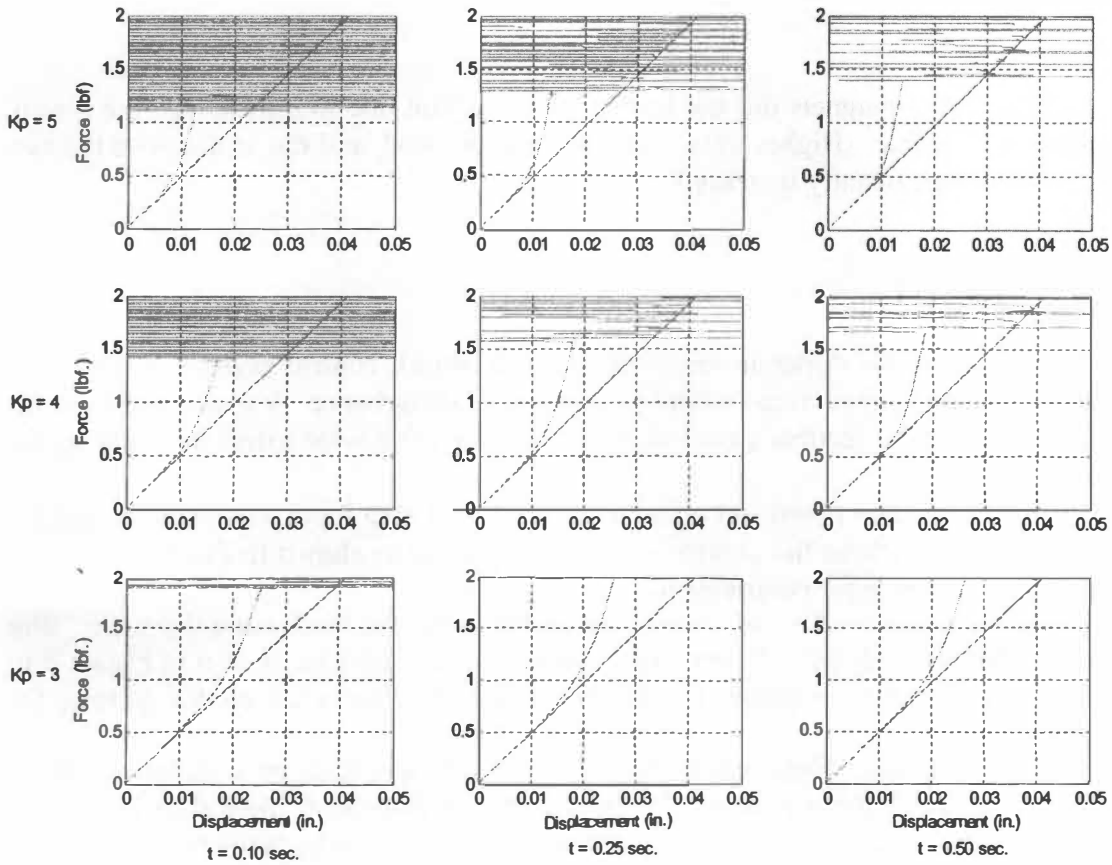


Figure 5-3 Force versus Displacement with Various Combinations of Kp and *t*

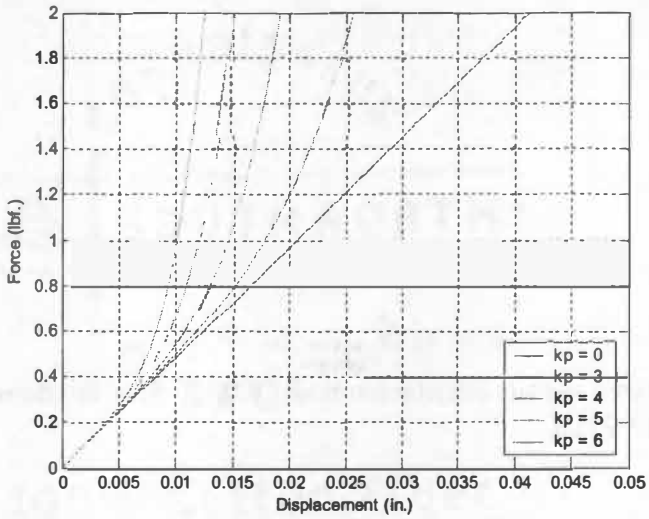


Figure 5-4 Stiffness of Saw Blade with Various Values of Kp when the Time Constant of the Electromagnets is Zero

If the electromagnets did not have a time constant due to inductance, the system was completely stable. Higher values of *Kp* could be used, and the stiffness of the saw blade could be significantly increased.

5.3 STEP INPUT

To examine the dynamic response of the feedback control system, a step input was applied to the mathematical model as an external disturbance. Various values of *Kp* and *t* were used in the feedback control system to determine what effect they had on the response.

Initially, *Kp* and *t* were set equal to zero. A unit step input was applied, and the dynamic response without the control system was plotted as shown in Figure 5-5. This was used as a reference for comparison.

Various values of *K*p and *t* were then added to the feedback control system. The dynamic responses with the different combinations of Kp and t are shown in Figure 5-6. The reference dynamic response of the saw blade was included on the graphs for comparison.

The steady state displacement of the saw blade was reduced with the feedback control system. High gains reduced the steady state displacement more than low gains. As in the stiffness test, as the gain increased the saw blade began to oscillate.

The time constant of the low-pass filter could be increased to increase the stability of the system. However, the disadvantage of increasing the time constant is it slows down the response time of the system. It is evident in the graphs that it took longer for the electromagnets to reduce the displacement with the higher time constants.

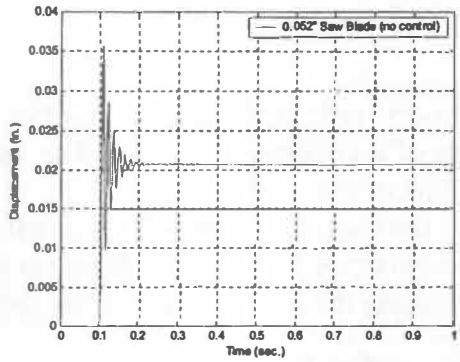


Figure 5-5 Displacement of Saw Blade to a Unit Step Input without Control System

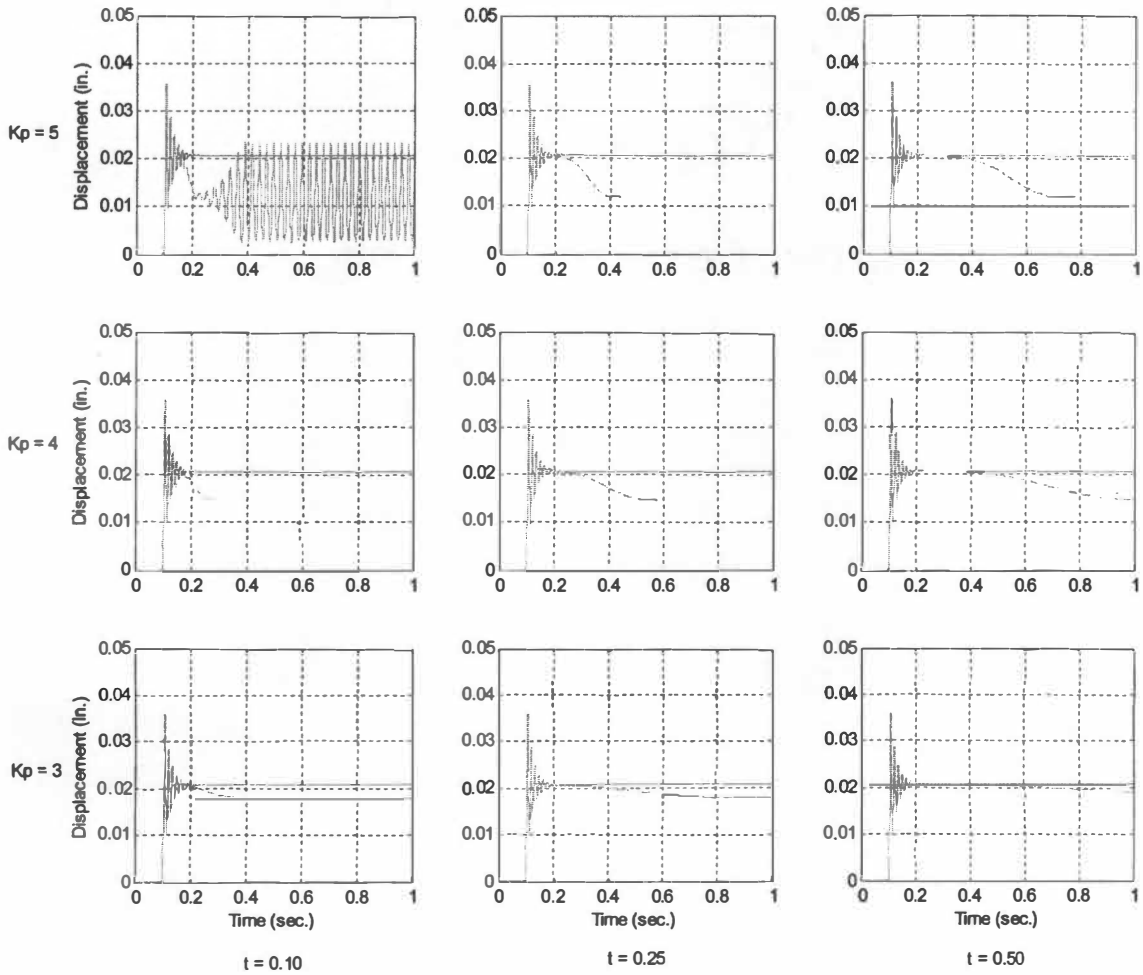


Figure 5-6 Displacement of Saw Blade to a Unit Step Input with Control System On

5.4 CONCLUSIONS

The mathematical model indicated that the feedback control system could possibly increase the stiffness of a circular saw blade. The amount that the stiffness is increased depends on the amount of proportional gain.

If the gain is too high, the control system will go unstable and the saw blade will begin to oscillate. The time constant of the low-pass filter can be increased to reduce the oscillation. However, by increasing the time constant of the low-pass filter, the output of the control system is delayed.

6 Prototype Design

A prototype of the feedback control system was designed and built to verify that it could increase the stiffness of a circular saw blade. The three main components of the feedback control system were a proximity transducer system, a bipolar operational power supply, and two electromagnets. The structure of the feedback control system is shown in Figure 6-1.

The following sections cover the design of the control system and the mounting used to put the electromagnets and proximity probe on a table saw. In conclusion, a picture of the complete prototype is shown.

6.1 CONTROL SYSTEM

Proximity Transducer System

A proximity transducer system was used to measure the position of the saw blade. The output of the proximity transducer system was an analog voltage that was proportional to the distance between the probe and the saw blade. The rated frequency response of the proximity probe was 10K Hz. at –3.0dB. The proximity transducer system provided the feedback to make the control system a closed loop.

Bipolar Operational Power Supply

A bipolar operational power supply (BOP) was used as a proportional controller and power supply in the feedback control system. A simplified diagram of the BOP is shown in Figure 6-2.

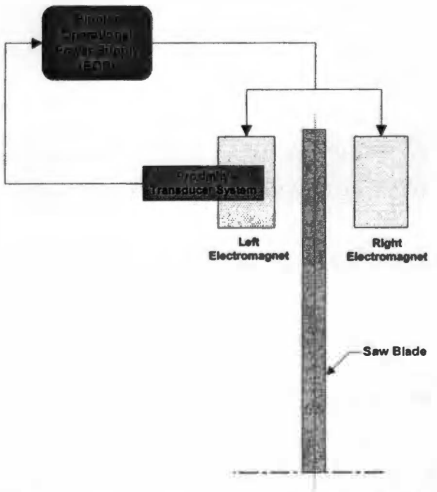
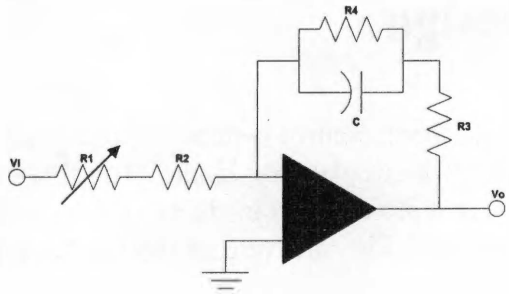


Figure 6-1 General Structure of the Feedback Control System Used on Prototype



Vi = input voltage from proximity transducer system
Vo = output voltage of the bipolar operational amplifier
R1 = external potentiometer
R2 = internal resistor
R3 = internal resistor
R4 = external resistor
C = external decade capacitor box

Figure 6-2 Simplified Diagram of the BOP

A low-pass filter was added to the control system by adding an external resistor *R4* and capacitor *C* to the feedback loop of the op-amp. The resistance *R4* was 102.2K Ω. A decade box was used for the capacitor *C*. The capacitance could be adjusted from 1μF to 10μF in steps of 1μF. This allowed the time constant *t of* the low-pass filter to be adjustable from 0.1 seconds to 1.0 second.

The proportional gain of the op-amp was

$$G = R_f / R_i \qquad \text{Equation (5.1)}$$

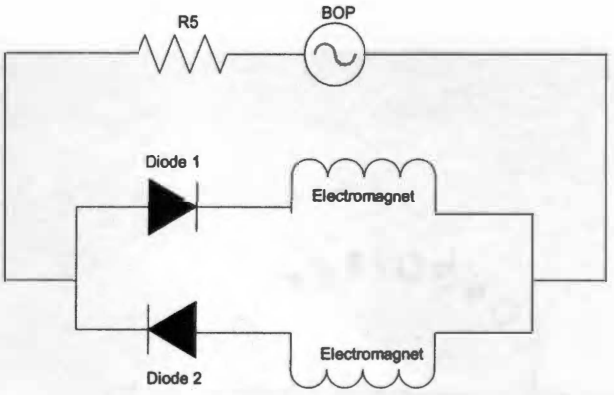
where

R_f = *equivalent feedback resistance*
R_i = *equivalent input resistance*

An external potentiometer R1 was added to the input of the op-amp to allow the gain to be adjustable.

Electromagnets

The circuit shown in Figure 6-3 was used to connect the electromagnets to the output terminals of the bipolar operational amplifier. The polarity of the terminals switched depending on which way the saw blade deflected. The diodes were used to direct the current to the correct electromagnet for the specific displacement of the saw blade. This prevented the electromagnets from both receiving current at the same time. The electromagnets could not be on simultaneously.



R5 = equivalent resistance of the circuit

Figure 6-3 Circuit Diagram Used to Connect the Electromagnets to the BOP

6.2 MOUNTING

A finite element analysis showed that the electromagnets needed to be placed directly under the table and near the edge where the uncut material first meets the saw blade. However, there was not enough space under the table on the table saw to mount the electromagnets. The decision was made to mount the electromagnets above the table and verify that the feedback control system could increase the stiffness of the saw blade. If so, then the table saw could be modified in the future to create space.

The bracket that was designed to mount the electromagnets above the table is shown in Figure 6-4. The proximity probe could be mounted directly above the electromagnet or to the side of the electromagnet on the aluminum plate. The bridge of the bracket was made adjustable in the vertical direction. The electromagnets could be moved in and out away from the side of the saw blade by screwing the small shaft into the L-bracket. A closer look at the electromagnet assembly is shown in Figure 6-5.

6.3 CONCLUSIONS

The prototype of the feedback control system mounted on a table saw is shown in Figure 6-6. A PC was used to collect and display data with Hp-VEE.

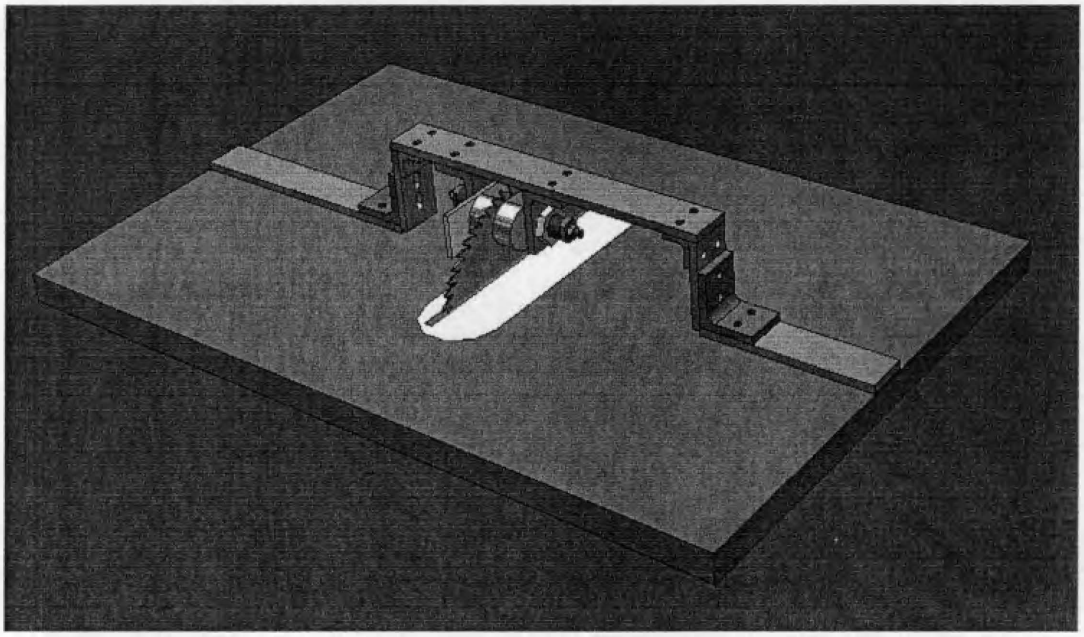


Figure 6-4 Bracket Designed to Mount Electromagnets and Proximity Probe on Table Saw

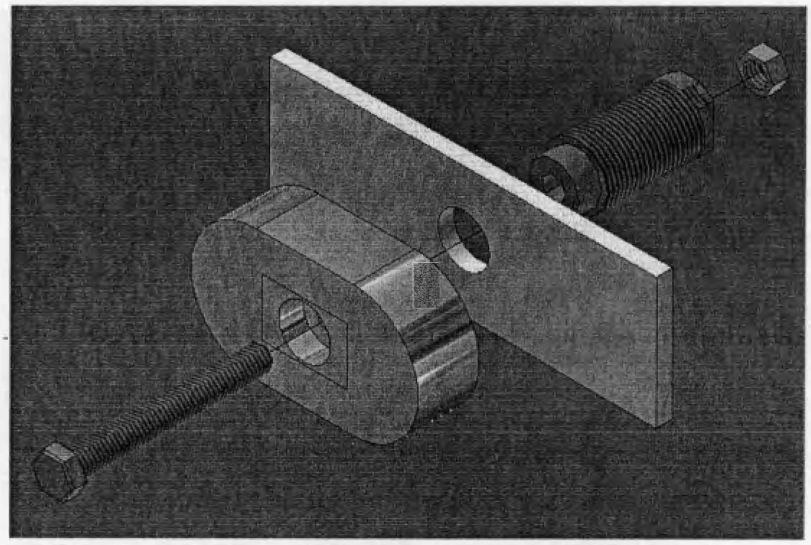


Figure 6-5 Assembly View of the Electromagnet Mount

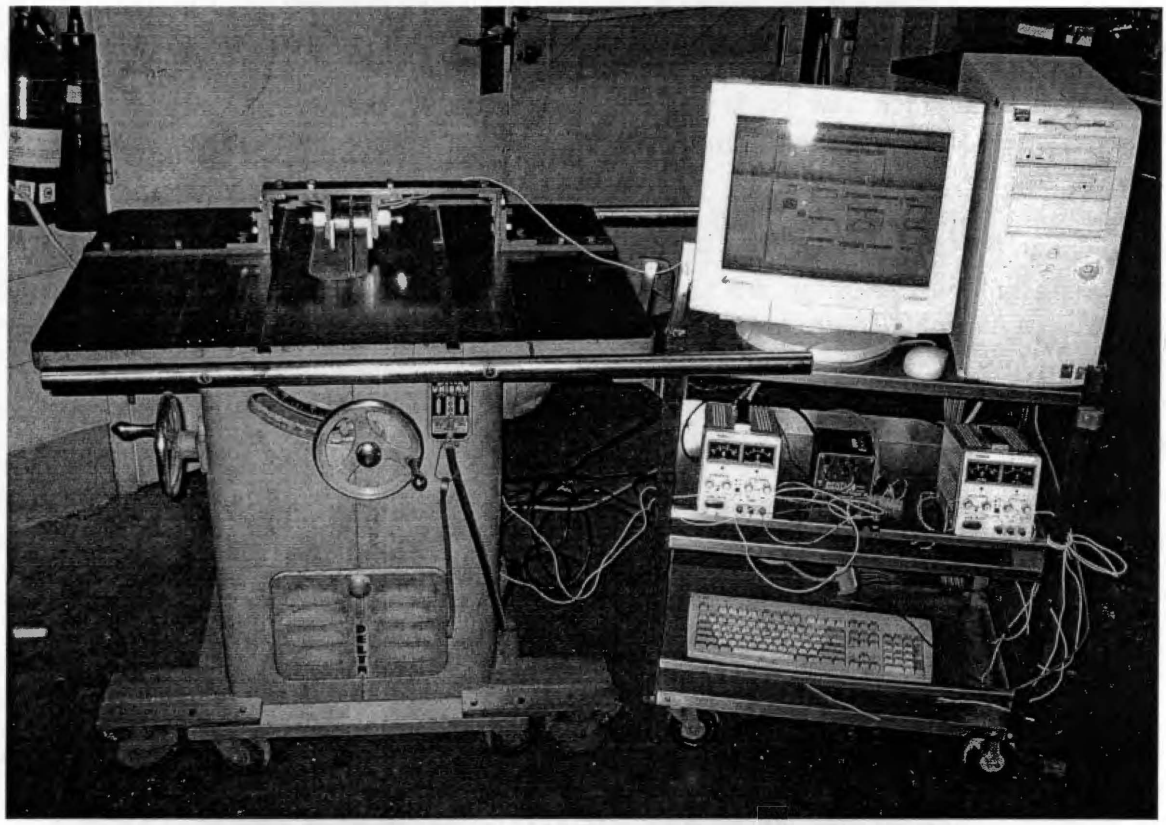


Figure 6-6 Prototype of Feedback Control System on Table Saw

7 Testing of Prototype

A prototype of the feedback control system was tested on a table saw to determine if it could increase the stiffness of a circular saw blade. The objective was to apply an external force to the side of a saw blade and measure its displacement with and without the control system. The magnitude of the force versus the displacement was plotted to determine how effective the feedback control system was in increasing the stiffness.

7.1 EXPERIMENTAL

Setup

A 0.052" thick saw blade was mounted onto the shaft of a table saw. Two electromagnets and a proximity probe were mounted relative to the saw blade as shown in Figure 7-1.

A shim was used to set the initial distance between the electromagnets and the saw blade to 0.05". The proximity probe was mounted beside one of the electromagnets and 0.06" from the side of the saw blade. The bias adjustment on the bipolar operational power supply was set to produce an output voltage of 0 volts with the saw blade in its initial position. Therefore, the bipolar operational power supply would only produce an output voltage when the saw blade was displaced from its initial position.

Procedure

With the control system turned off, a force gage was used to apply forces on the side of the 0.052" thick saw blade as shown in Figure 7-2. The forces were applied at the

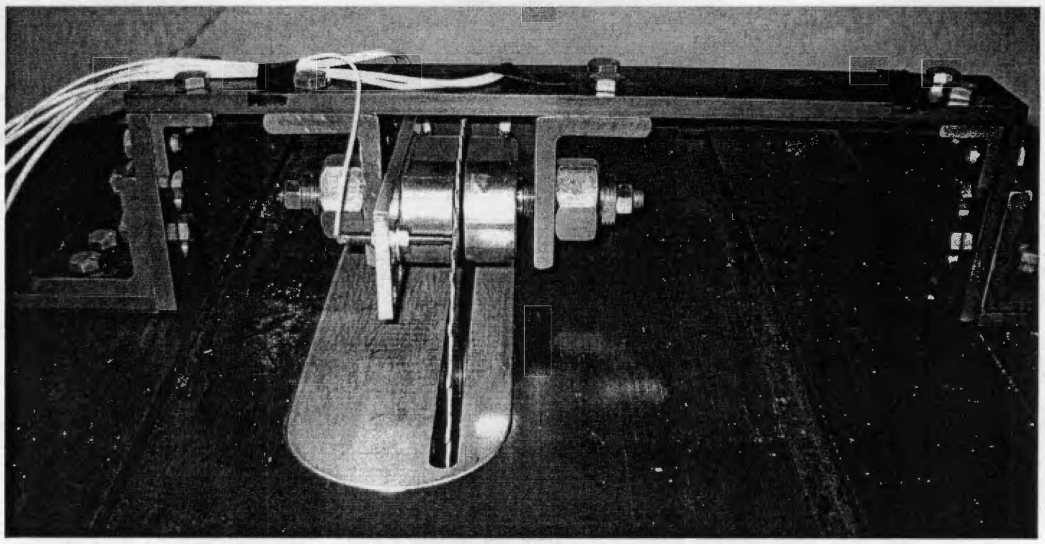


Figure 7-1 Mounting of Electromagnets and Proximity Probe on Table Saw

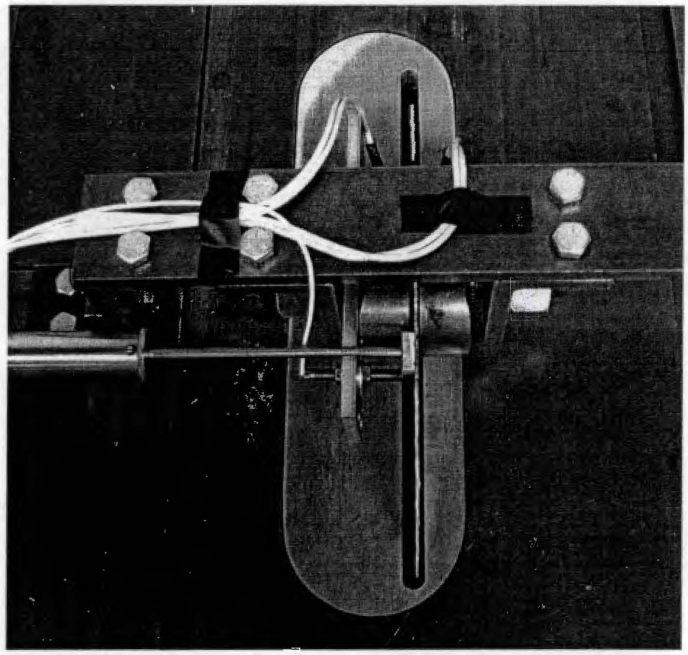


Figure 7-2 Force Gage was Used to Apply an External Force on Saw Blade

outer edge of the saw blade and directly above the proximity probe. The displacements of the saw blade due to the forces were measured with the proximity probe and recorded in Hp-VEE. The magnitude of the forces ranged from 1 to 3.5 lb.

This same procedure was repeated with the 0.065" thick saw blade. Both sets of data were used as references to compare the effectiveness of the feedback control system.

The control system was then turned on. Initially the time constant *t* of the low-pass filter was set equal to zero, and the proportional gain *Kp* of the op-amp was set to one. The force gage was used to apply forces from 1 to 3.5 lb to the side of the saw blade. If the saw blade did not oscillate, then *Kp* was increased. When the saw blade did begin to oscillate, *t* was increased until the saw blade stopped oscillating.

The procedure was repeated until no combination of *Kp* and *t* would allow 1 to 3.5 lb to be applied to the saw blade without it oscillating. The objective was to determine what combination of *Kp* and *t* could be used to increase the stiffness of the saw blade the most.

7.2 RESULTS

The force versus the displacement for the 0.052" thick saw blade is shown in Figure 7-3. The time constant *t* of the low-pass filter was increased as the proportional gain *Kp* was increased in order to prevent the saw blade from oscillating.

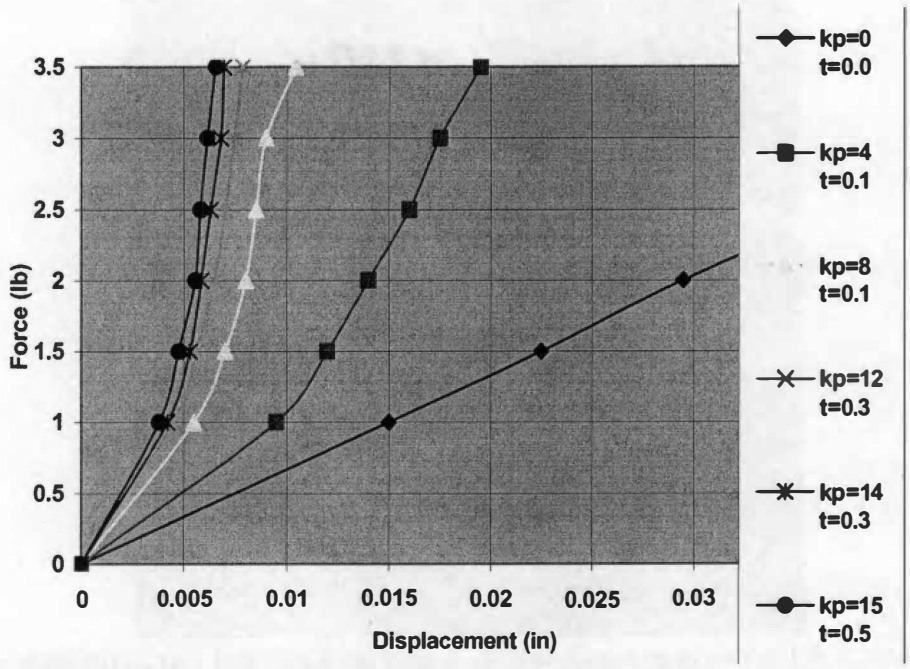


Figure 7-3 Force versus Displacement for 0.052" Thick Saw Blade With and Without Feedback Control

Equation (7.1) was used to approximate the stiffness of the saw blade from the experimental data:

$$k = (F_2 - F_1)/(x_2 - x_1) \qquad \text{Equation (7.1)}$$

where

F_i = *force applied to saw blade*
x_i = *displacement of saw blade due to* F_i

Table 7-1 shows the stiffness of the saw blade with and without the control system. The stiffness was calculated in "force ranges" because the stiffness changed as the magnitude of the force was increased.

Equation (7.2) can be used to calculate the equivalent thickness t_2 of the 0.052" thick circular saw blade from its equivalent stiffness k_2 with the control system and its equivalent stiffness k_1 without the control system

$$t_2 = (k_2 / k_1)^{1/3} * t_1 \qquad \text{Equation (7.2)}$$

where

k_2 = *stiffness with control system*
k_1 = *stiffness without control system*
t_1 = *actual thickness of circular saw blade*

Table 7-1 Stiffness of 0.052" Thick Saw Blade with Control System

	Equivalent Stiffness (lb/in)					
Force Range (lb)	*Kp = 0*	***Kp = 4***	***Kp = 8***	***Kp = 12***	***Kp = 14***	***Kp = 15***
(0 - 1)	70	105	189	222	238	263
(1 - 2)	70	222	400	500	606	571
(2 - 3)	70	286	1000	1053	1053	1667

The equivalent thickness t_2 of the 0.052" thick saw blade with the control system is given in Table 7-2.

To show the effectiveness of the feedback control system, the displacement of the 0.065" thick saw blade without the control system was plotted on the same graph as the displacement of the 0.052" saw blade with the control system. The results are shown in Figure 7-4.

7.3 CONCLUSIONS

The feedback control system can increase the stiffness of a circular saw blade. The amount that the stiffness is increased depends on the proportional gain of the system. The stiffness of the saw blade increases as the gain is increased. However, the amount of gain is limited because the saw blade starts to oscillate.

Stability can be added to the system by increasing the time constant of the low-pass filter. This reduces the oscillation of the saw blade. However, it delays the output of the feedback control system.

Table 7-2 Equivalent Thickness of 0.052" Thick Saw Blade with Feedback Control System

	Equivalent Thickness				
Force Range (lb)	***Kp = 4***	***Kp = 8***	***Kp = 12***	***Kp = 14***	***Kp = 15***
(0 - 1)	0.060"	0.072"	0.076"	0.078"	0.081"
(1 - 2)	0.076"	0.093"	0.100"	0.107"	0.105"
(2 - 3)	0.083"	0.126"	0.128"	0.128"	0.150"

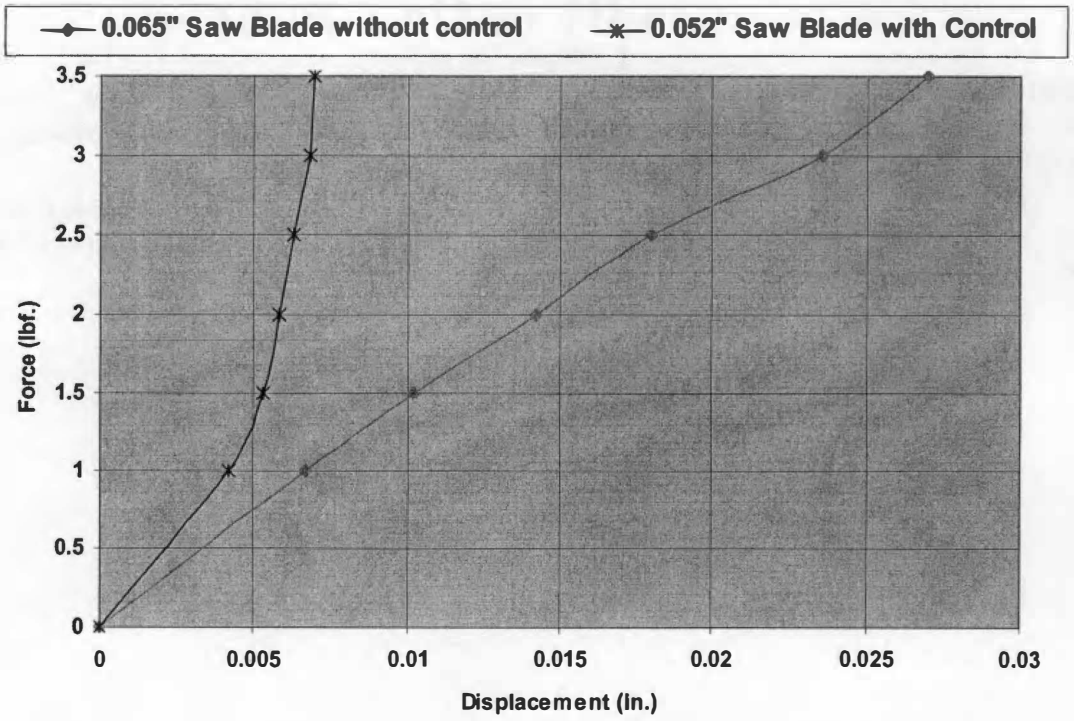


Figure 7-4 Stiffness Comparison of 0.065" Thick Saw Blade without Feedback Control and 0.052" Saw Blade with Feedback Control

8 Conclusions

8.1 RESULTS

A feedback control system employing electromagnets was developed to increase the stiffness of a circular saw blade. The feedback control system had two adjustments:

1. Amount of proportional gain *Kp*
2. Time constant *t* of low-pass filter in the feedback loop.

By adjusting these two parameters, the system could be tuned to maximize the equivalent stiffness of a circular saw blade.

A prototype of the feedback control system was tested on a table saw. A force gage was used to apply an external force on a 0.052" thick saw blade with and without the control system on with various gains and time constants. The displacement of the saw blade was measured and plotted versus the magnitude of the force. The equivalent stiffness of the saw blade was calculated and shown in Table 8-1.

With the feedback control system, the stiffness was not linear. Therefore, the stiffness was calculated over a "force range" as indicated in the table.

The equivalent stiffness of the saw blade with the feedback control system was used in the equation

$$t_2 = (k_2 / k_1)^{1/3} * t_1 \qquad \text{Equation (8.1)}$$

where

k_2 = *stiffness with control system*
k_1 = *stiffness without control system*
t_1 = *actual thickness of circular saw blade*

to calculate the equivalent thickness. The equivalent thickness of the 0.052" thick saw blade with the feedback control system is shown in Table 8-2.

Table 8-1 Equivalent Stiffness of 0.052" Thick Circular Saw Blade With and Without Feedback Control System

	Equivalent Stiffness (lb/in)					
Force Range (lb)	***Kp = 0***	***Kp = 4***	***Kp = 8***	***Kp = 12***	***Kp = 14***	***Kp = 15***
(0 - 1)	70	105	189	222	238	263
(1 - 2)	70	222	400	500	606	571
(2 - 3)	70	286	1000	1053	1053	1667

Table 8-2 Equivalent Thickness of a 0.052" Thick Circular Saw Blade with the Feedback Control System

	Equivalent Thickness				
Force Range (lb)	***Kp = 4***	***Kp = 8***	***Kp = 12***	***Kp = 14***	***Kp = 15***
(0 - 1)	0.060"	0.072"	0.076"	0.078"	0.081"
(1 - 2)	0.076"	0.093"	0.100"	0.107"	0.105"
(2 - 3)	0.083"	0.126"	0.128"	0.128"	0.150"

The feedback control system made the stiffness of the 0.052" saw blade equivalent to a saw blade up to twice its thickness. If this could hold true when the saw blade is cutting wood, a 0.052" thick saw blade could cut as if it were a 0.150" saw blade. This would be more than a 50% reduction in wasted material.

8.2 FUTURE CONSIDERATIONS

The following tasks should be performed in the future to improve the current design of the feedback control system and to help determine its effectiveness in increasing the stiffness of a circular saw blade:

- The feedback control system needs to be tested while a circular saw blade is cutting. The circular saw blade needs to bend while cutting during the test. This may require a thinner saw blade to be used.

- The feedback control system needs to be tested with the electromagnets under the table of the saw instead of above the table. A pair of electromagnets could be placed directly below the table and near the edge where the uncut material first meets the saw blade. Another pair of electromagnets could be placed symmetrically on the other edge of the saw blade.

- A higher order low-pass filter could be used instead of a first order low-pass filter. This would allow the cutoff frequency of the filter to be increased therefore increasing the output response of the feedback control system. With the first order low-pass filter, the cutoff frequency had to be low enough to ensure that the high frequencies were attenuated enough to not affect the output of the system.

- A more advanced control method needs to be tested with the feedback control system. The magnetic force of an electromagnet is non-linear with respect to

current and distance. A non-linear control method may be able to compensate for the non-linearity and improve the effectiveness of the feedback control system.

- The mathematical model representing the feedback control system needs to be improved to provide results that correlate with the prototype results. The dynamic characteristics of the model and the prototype were the same, but the values for the proportional gain, time constant of low-pass filter, and the magnitude of deflection did not correspond. Experimentally determining the parameters for each component of the system again and using them in the model could improve this.

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Vita

Nicholas M. Sullivan grew up in the central Kentucky area and attended Eastern Kentucky University (EKU). At EKU, he played football and was a four-year starter and team co-captain. Throughout his last semester, Nicholas worked at Toyota Motor Manufacturing Kentucky for six months as a co-op. After five years, Nicholas received a Bachelors of Science degree in Engineering Physics with a minor in Mathematics.

After graduating from EKU, Nicholas moved to Knoxville, Tennessee. He went to graduate school at the University of Tennessee (UT). Nicholas attended UT for two years before receiving a Masters of Science degree in Mechanical Engineering with a concentration in Design.

Upon graduation, Nicholas moved back to the central Kentucky area. He accepted a job offer from Lexmark International to work as a Hardware Engineer.

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