DEVELOPMENT OF NON-INTERFERING WOUND-ON-TENSION MEASUREMENT METHOD

By

WENXING JIANG

Bachelor of Science in Mechanical Engineering

Oklahoma State University

Stillwater, OK

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DEVELOPMENT OF NON-INTERFERING

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Thesis Approved:

Dr. J. K. Good

Thesis Adviser

Dr. R. P. Singh

Dr. H. Hatami-Marbini

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Abstract: The key element to understand the structure of a wound roll is the pressure inside it. This pressure cannot be too small or too large. If it is too small it may not withhold its structure. If it is too large it may damage the material. Researchers have spent decades on developing winging model to predict this inner pressure. Wound on tension, which is the stress occur in the outer layer of a roll during winding, have been proved to be one important parameter relates with the inner pressure of roll. Several methods are developed to measure this parameter. The accuracy of a common used interfering measurement method will be evaluated and a non-interfering measurement will be developed in this paper.

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E_{11},E_{22},E_{33}	modulus of web in 1,2,3 direction respectively
Ec	core stiffness
E_r, E_θ	radial, tangential modulus of the web
h	web thickness
K_1,K_2	constants in Pfeiffer's equation (Eqn2.9)
N	nip load per unit width
P_c	compressive pressure
Tw	tensile stress in web
s	current outer layer radius
w	radial displacement
R	radius
Rc	core outer radius
μ	coefficient of friction
σ_{ri}	radial stress in ith lap
$\delta\sigma_r$	incremental radial stress
$\delta\sigma_\theta$	incremental tangential stress
δw	core deformation
ε_c	compressive strain
ε_θ	radius strain

CHAPTER I

INTRODUCTION

Webs used in roll-to-roll manufacturing processes are stored in wound rolls as the web awaits subsequent processing. The wound roll is the only means known that can be used to store great lengths of web. Webs are quite delicate in free form but when wound into rolls the web is protected from edge damage.

Wound rolls of web must have sufficient internal pressures and stress to maintain the structural integrity of the roll. The interlayer frictional forces due to pressure and friction must be sufficient to prevent internal slippage during storage, transport and unwinding. Pressures and stresses within the wound roll can be so high that web quality is deterred. Inelastic deformation results in problems when unwinding for subsequent processing. Sticking defects called wringing or blocking may prevent unwinding altogether and must be avoided.

Wound roll models and experimental tests have been developed to provide the ability to forecast and verify the pressures and stresses within wound rolls. While these models are now at a high level of development and sophistication their applicability to wide ranges of web materials and winding equipment is not robust. The test method developed to date also have limitations. Good methods that do not interfere with the wound roll pressures are almost non-existent.

The research reported herein will discuss the development of a new method which is the combination of a winding model and a test method. This new method is robust in that it can be applied to a wide range of web materials and winding equipment while not interfering with the pressures and stresses that must be determined.

CHAPTER II

BACKGOUND, LITERATURE SURVEY AND RESEARCH OBJECTIVE

This research involves bringing together knowledge of winding machines, winding models and test methods to develop new combined methods to forecast the internal stresses within wound rolls.

2.1 Background of Winding Equipment

Many winders may look mechanically similar but in operation they are very different and can induce very different pressures and internal stresses in wound rolls. Many winders involve the use of a nip roller as shown in Figure 2.1. Winding occurs at speeds where air entrainment into the wound roll is a concern. A loaded nip roller is used to reject as much of the entrained air as possible. Entrained air is undesirable as (1) airborne layers within the wound roll can telescope off the roll ends and (2) it can result in decreased pressure within the wound roll that causes storage and transportation defects.

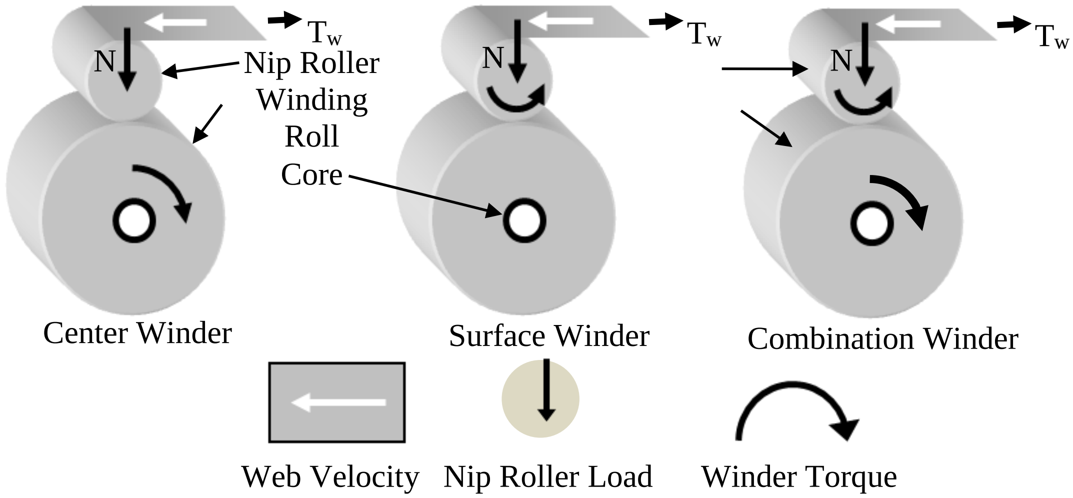

Figure 2.1 Winders

The nip roller impinging the wound roller also induces slippage in the outer layers of the winding rolls. The web tensile stress in the outer layer of the winding roll, called the Wound-On-Tension (WOT), can be very different than the tensile stress in the web prior to entry of the winder (T_w). Winding models and winding tests have proven that the WOT is the most influential parameter in determining the pressures and stresses within the wound roll. The web slippage and the resulting WOT is a function of complex contact mechanics. The slippage can be either promoted or inhibited by web material and surface properties, where the winding torque enters the winder (Figure 2.1) the nip roller load and the characteristics of the nip roller. This is why the winders shown in Fig. 2.1 can wind rolls with very different internal pressures and stresses.

2.2 Winding Models

The oldest winding model can be traced back to late 1950s. This model assumed the web material to be isotropic [1]. Most web materials have very different radial and tangential modulus. The differing modulus can be due to how the web was formed or due to the contact mechanics of the web surfaces and how they were formed. The radial modulus has been measured for many webs and proven to be non-constant and state dependent on the pressure or radial strain. All of the early models were attempts to produce closed form solutions for the internal stresses in the wound roll. These closed form solutions could not account for state dependent material properties.

The first one dimensional wound roll model that accounted for anisotropy and a state dependent modulus was created by Zig Hakiel[2]. The model is for center winding with no nip roller. This model predicts the radial and tangential stresses as a function of one dimension, the wound roll radius. This winding model integrated equilibrium, constitutive and compatibility equations. Hakiel assembled these equations into a second order differential equation written in terms of the incremental radial stresses due to the addition of the most recent layer of web added to the wound roll:

$$r^2 \frac{d^2\delta\sigma_r}{dr^2} + 3r\frac{d\delta\sigma_r}{dr} - \left(\frac{E_\theta}{E_r} - 1\right)\delta\sigma_r = 0 \quad (2.1)$$

Where r is the radius of wound roll

E_r is radial modulus

E_θ is tangential modulus

$\delta\sigma_r$ is the incremental radial stress

Being a second-order differential equation, two boundary conditions were required for solution. The first boundary condition employed was an inner boundary condition which is based on the inside of the innermost web layer having a compatible deformation with the outside of the core. Hakiel developed a core stiffness (E_c) parameter which related the radial stress presented on the core to the core deformation (δw):

$$\delta w/_r\,|_{r=r_c} = \frac{\delta\sigma_r}{E_c} \quad (2.2)$$

Where σ_r is Radial Pressure

w is radial displacement

r is radius

r_c is core outer radius which equals to roll inner radius

The radial deformation of the core was then set equal to the radial deformation of the innermost web layer normalized by the layer radius, also taken as r_c:

$$\epsilon_\theta = {}^{\delta w}/_{r}\,|_{r=r_c} = \frac{\delta\sigma_\theta}{E_\theta} - \frac{\nu_{r\theta}}{E_r}\delta\sigma_r \quad (2.3)$$

By equating equations 2.2 and 2.3 and by use of the equilibrium equation in polar coordinates:

$$\delta\sigma_\theta = r * \frac{d\delta\sigma_r}{dr} + \delta\sigma_r \quad (2.4)$$

a derivative boundary condition is derived:

$$\left.\frac{d\delta\sigma_r}{dr}\right|_{r=r_c} = \left[\!\left[\frac{E_\theta}{E_c} - 1 + \nu_{r\theta}\right]\!\right]\frac{\delta\sigma_r}{r_c} \quad (2.5)$$

The second boundary condition is the outer boundary condition results from equilibrium of the current outer web wrap as it is added to the winding roll:

$$\delta\sigma_r|_{r=s} = -\frac{T_W}{S} * \text{h Equation} \quad (2.6)$$

Where $\delta\sigma_r$ is incremental pressure at r=s

T_W is the web tensile stress in the outer wrap

s is the current outer lap radius

h is web thickness

The differential equation (2.1) is solved with the boundary conditions of equations (2.5) and (2.6) using a finite difference approximate for the incremental radial stresses due to the addition of the most recent layer. The radial stress increments for each layer are then summed up with previous radial stress increments to obtain the total radial stress in each layer. The stress in i^{th} lap of wound roll can be represented as:

$$\sigma_{ri} = \sum_{j=i+1}^{n} \delta\sigma_{rij} \tag{2.7}$$

Where σ_{ri} is the total radial stress in i^{th} lap of wound roll

$\delta\sigma_{rij}$ is the pressure increment for each wrap

With the radial stress known as a function of radius the derivative can be estimated with respect to radius and the equilibrium equation can be used to determine the tangential stresses in each web layer:

$$\sigma_\theta = r * \frac{d\sigma_r}{dr} + \sigma_r \tag{2.8}$$

Application of Hakiel's model shows the tension in the outer layer has greater impact on wound roll stresses than any other parameter. The web radial and circumferential moduli are also influential but less so. The accuracy of these inputs is important.

Pfeiffer[3,4] recognized the nonlinear strain-stress behavior for stacks of paper in compression. He employed an exponential curve fit that has been found to model stacks of many web materials with good accuracy:

$$P_c = -\sigma_r = K_1[e^{K_2\epsilon_c} - 1] \tag{2.9}$$

Where P_c is the compressive pressure

ϵ_c is the compressive strain

K_1 is the pressure on sheets when strain is zero

K_2 is a dimensionless constant

Taking the derivative of Eq. 2.9 with respect to the compressive strain yields the radial modulus:

$$\frac{dP_c}{d\epsilon_c} = E_r = K_2[P_c + K_1] \tag{2.10}$$

Thus a linear dependence of the radial modulus on pressure is shown. In fact the dependence can be more complex but this representation has proven accurate for many webs. This form of the radial modulus has been incorporated into several winding models.

Two dimensional winding models were later developments. An early two dimensional model created by Kedl[5] was developed using a one dimensional model. Two dimension models are important because of the non-uniformity of web thickness over the web width and length. Kedl divided the web width into a finite number of segments and assigned each segment a web thickness that was representative of that segment. A one dimensional winding model was employed for each segment which was based upon the accretion of thick walled cylinders with orthotropic properties. The outer radius of each segment could vary across the roll width due to the variation in web thickness. It was assumed that all segments maintained one constant angular velocity. The variation in outer lap radius resulted in surface velocity variation. The outer lap tension was greater for those segments with larger radii in comparison to those with smaller radii. This model predicted the radial and circumferential stresses as a function of radial and widthwise location. This model was known as a pseudo 2D model since wound roll stresses were modeled in two dimensions through the use of a 1D winding model for each segment. A similar pseudo model was developed by Cole and Hakiel[2]. Hakiel introduced the concept of relaxation radius to parse the web tension across the web width. They assumed that for a web with non-uniform thickness, when a new layer was wound onto the roll, that the new layer may not make full contact with the previous layer of web beneath it. Some segments may have no contact, the radius to the centerline of these segments was defined as the relaxation radius. Each segment was then modeled using Hakiel's one dimensional winding model algorithm [2]. Hakiel and Cole developed the first segmented instrumented core which could be used to determine the core pressure in each segment. They verified their pseudo 2D winding model by comparing model and test values of core pressure.

Psuedo models model each segment of web independently and neglect the compatibility of deformation of a given web layer as it passed from one sector to another. In other words, these two models suffer from a lack of continuity across the width direction of web. In later research, Hoffecker and Good[7], Lee and Wickert[8,9], and Mollamahmutoglu [26] developed axisymmetric models that allow a continuous widthwise variation of thickness and tension. These models differ in how new layers are accreted to the wound roll and how tension is allocated across the web width. Axisymmetric quadrilateral elements were used these finite element winding models. In axisymmetry, the web layer is modeled with elements in the RZ plane and then spun about the Z axis in θ direction to form a three dimensional toroid(Figure2-2).

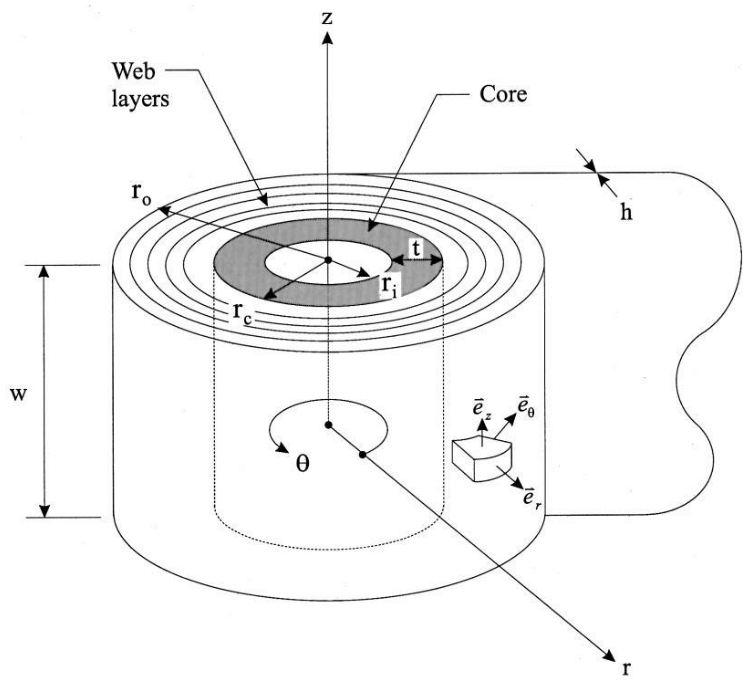

Figure 2-2 Axisymmetric winding model

2.3 WOT Studies

In the *Winding Equipment Background* a discussion of the use of nip rollers that are impinged into winding rolls was given. The nip induces slippage in the outer layer(s) of a winding roll that affect the tension in the outer layers. Pfeiffer was first in documenting this effect by winding rolls of paper with an impinged nip and then using a destructive method called the Cameron Gap test to document that the nip roller had in fact elevated the tangential strains and outer layer tensions above the tension of the web upstream of the winder [3]. Pfeiffer also documented this effect in the laboratory by rolling nip rollers over stacks of paper webs and monitoring the slippage and tension induced in the layers [4]. Pfeiffer also created an unwinding/winding laboratory machine that measured Wound-Off-Tension from the outer layer of an unwinding roll and Wound-In-Tension from the outer layer of a surface wound roll [10]. The Wound-In-Tension was measured by passing the web over a roller supported by load cells after exiting the nip roller and then returning the web to the surface of the winding roll. The Wound-Off-Tension was measured in a similar fashion. From this device Pfeiffer was able to demonstrate how changes in web tension and nip load changed the tension in the outer layer of a winding roll. Based on these early works it was known that the slippage between layers and the changes in web tension induced by the rolling nip involved contact mechanics.

Good and Wu [11] used finite element modeling to understand the development of the web tensions induced by nip rollers called Nip-Induced-Tension (NIT). Good, Wu and Fikes [12] also conducted center winding tests where pressure sensors were wound into the rolls for various webs and nip loadings. Through their work they found that the upper bound for the NIT was limited by friction forces between the outer layer and the layer beneath the impinged nip. They suggested the use of equation (2-12) for calculation of the NIT:

$$NIT = \frac{\mu N}{h} \tag{2.12}$$

Where N is the nip loading per unit width, h is the web thickness and μ is the coefficient of friction between web layers. Also when center winding with a nip they proposed a relationship between NIT, web tension (T_w) and the WOT in equation 2.13:

$$WOT_{center\ winding\ with\ a\ nip} = NIT + T_W \tag{2.13}$$

Furthermore they proposed the expression for WOT could be used as a new outer boundary condition for extending the use of center winding models to center winders with nip rollers. The outer boundary condition given in equation 2.3 in Hakiel's winding model was modified to:

$$\delta\sigma_r = -(T_W + \frac{\mu N}{h}) * \frac{h}{S} \tag{2.14}$$

Use of this new boundary condition with Hakiel's winding model produced in roll pressures that were consistent with pressures measured within center wound rolls that were wound with the presence of a loaded nip roller. Equation 2.13 is however an upper bound for the WOT, it can be less. Steves conducted surface winding tests of newsprint webs [13] and found at low nip loadings that the only WOT was the nip induced tension (NIT):

$$WOT_{surface\ winding} = NIT = \frac{\mu N}{h} \tag{2.15}$$

This WOT could be integrated into the outer boundary condition as well to model surface winding with Hakiel's model and it would work well for low nip loadings. At higher nip loadings the proportionality between nip load and WOT became less than the coefficient of friction and for some webs the WOT could become independent of nip loading. Center and surface winding tests on Tyvek demonstrated this [20].

Hartwig discovered that the WOT measurement method invented by Pfeiffer was an interfering test [15]. He determined this by winding rolls in which he inserted pressure sensors and then using a winding model. Hartwig would vary the WOT in the outer lap until the winding model produced the pressures measured in the wound roll. He then wound rolls and made WOT measurements using the method of Pfeiffer. He found that the WOT inferred from a winding model was greater than that measured by Pfeiffer's method. It was concluded that Pfeiffer's method interfered with the WOT by allowing web slippage between the web exit of the nip roller and the point at which the web was extracted from the winding roll to make the WOT measurement. Good, Kandadai and Markum found that non-interfering WOT measurements could be made by using laser Doppler velocimeters to measure the NIT which could then be added to the web tension [16]. This method was difficult to employ as one of the velocimeters must be used to measure the surface velocity of the wound roll after the web exits the nip roller.

Gains were also being made in computing the WOT using codes that modeled the contact mechanics of the web transported about the nip roller, into the convergence of the nip and wound roll and the web after exiting the nip roller. Jorkama was first to model part of this behavior [17]. Kandadai was the first to model center winding with a nip by computer simulation of the entire winding process [18]. Ren was the first to model center and surface winding while incorporating the state dependent material properties [19]. At this point modeling of the contact mechanics in winding has achieved a high level of sophistication.

2.4 Research Objectives

There are two objectives of this research:

1. To provide better understanding of why the WOT measurement developed by Pfeiffer interferes with the WOT. The results of this research will help develop new non-interfering methods.
2. To develop a non-interfering WOT measurement that could be easily employed in a laboratory or production environment. Such measurements would be useful to those who study WOT using computer simulations and those who wish to conduct empirical simulations of WOT in industry.

CHAPTER III

INTREFERING/DIRECT WOT MEASUREMENT METHOD

3.1 Introduction

In the *WOT Studies*, Pfeiffer's WOT measurement method have been discussed and this method have been proved by Hartwig[15] to be an interfering test. To gain a better understanding of why Pfeiffer's method is an interfering method, the parameters which are brought in to winding mechanism because of added rollers should be investigated. These parameters can be seen in figure 3-1 and they are:

1. Wrap Angle, the angle of wrapping area between the point where web leave nip and the point where web leaves winding roll.
2. Web travel distance, the distance between where web leaves the winder and the point where web enters "WOT measuring zone"
3. Wing velocity, the parameter that decides how fast the web will wind back to the winding roll.

The experiments conducted to investigate these parameters are discussed in the following sections.

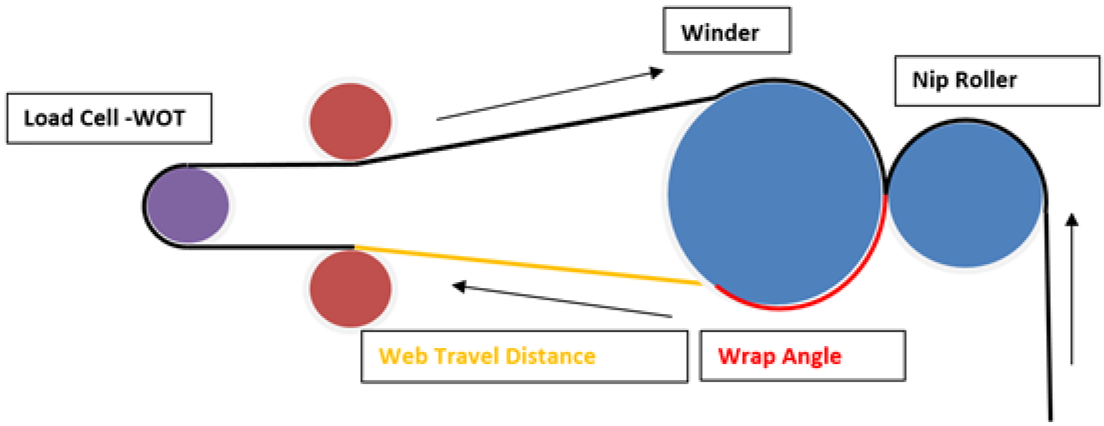

Figure 3-1 Parameters investigated for Pfeiffer's WOT measurement method

3.2 Experimental Setup for Pfeiffer's WOT Measurement Method

The cantilever winding apparatus in Web Handling Research Center here at Oklahoma State University is used as showing in Figure 3-2. Starting from the unwind zone with an unwind roll, the web tension is provided by a magnetic hysteric brake. The web is guided by a displacement guide to control the lateral position of web. An idler roller mounted on a load cell measures web tension. Web tension is controlled with a PID controller using the tension measurement as a feedback to control the current to the hysteretic break. The web then passes onto the rip roll shown in figure 3-1 and enters the winder. This nip roll pivots on a swing arm and mounts on a sled. Nip load is monitored by computer and controlled by adjusting the internal pressure in pneumatic cylinders. After leaves nip roll, the web becomes the outer layer of the winding roll. As shown in figure 3-1, the web is extracted from the surface of the winding roll. The web then transits a set of three rollers where the wound-on-tension is measured prior to returning the web to the surface of the unwinding roll.

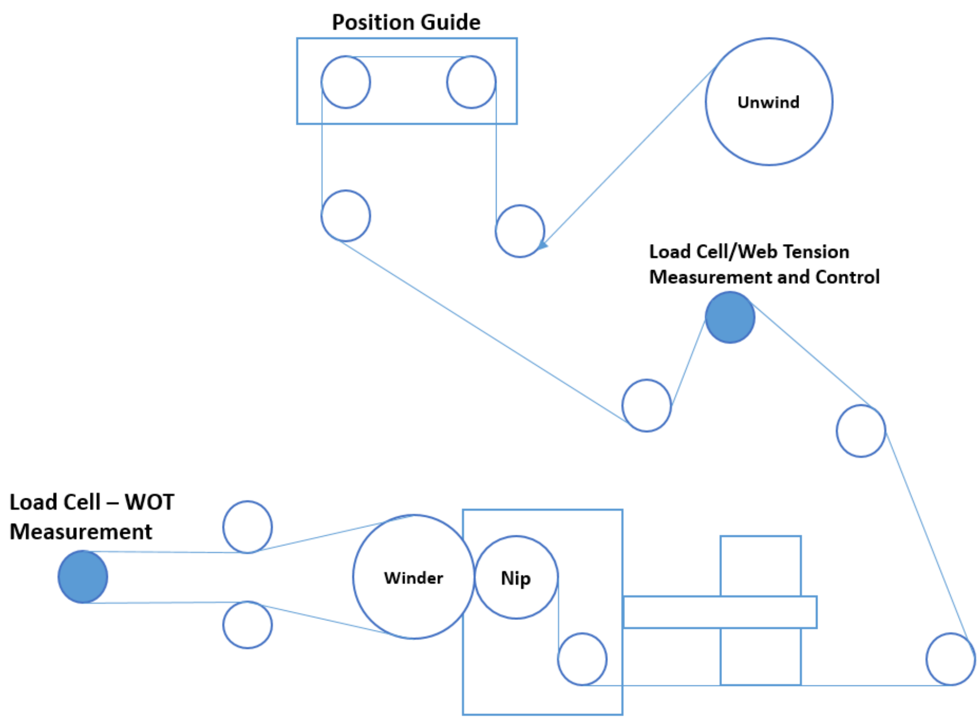

Figure 3-2 Apparatus for Pfeiffer's WOT measurement method

In this experiment, bond paper with a 6 inch width was used as the web material. A web tension of 3 pli was applied. An aluminum roller with a 4 inch outer diameter was used as the nip roll. The web was wound on a steel core 3.2 inches in outer diameter. In a typical test the wound roll radius increased from 1.6 to 4.6 inches. The increase in wound roll radius is called "pile height" and was 3 inches in these tests. During the winding process, nip load, web tension and WOT were all recorded.

3.3 Results and Discussion.

3.3.1 Impact of Wrap Angle

To investigate wrap angle, the experiment was designed by moving the WOT measuring rollers to two machine allowable positions where maximum wrap angle and minimum wrap angle could be achieved. These two positions could be seen in figure 3-3. The first position had a web wrap angle of 220 degrees and the second position had a web wrap angle of 20 degrees.

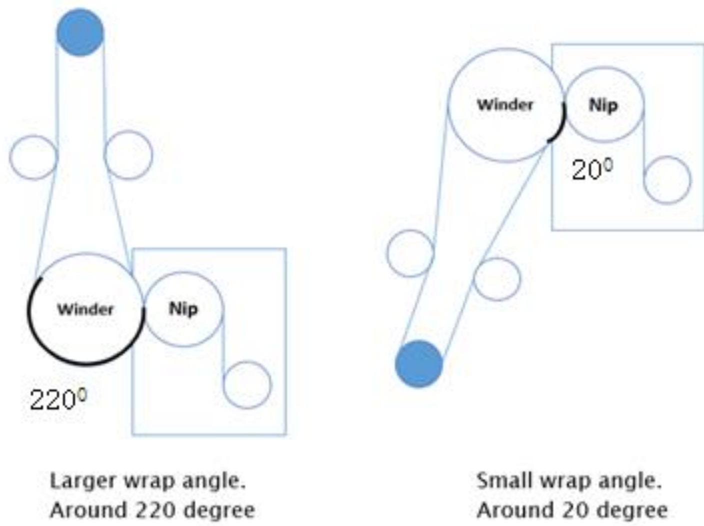

Figure 3-3 Experiment designed to investigate wrap angle

The test results are shown in figure 3-4. The vertical axis represents WOT value during winding. The Horizontal axis represents the web pile height. The blue data represents recorded results for winding with a 20 degree wrap angle with three different nip loads. The red data represents recorded results for winding with a 220 degree wrap angle with three different nip loads. The results indicate that when winding with smaller wrap angle, a higher WOT value is measured.

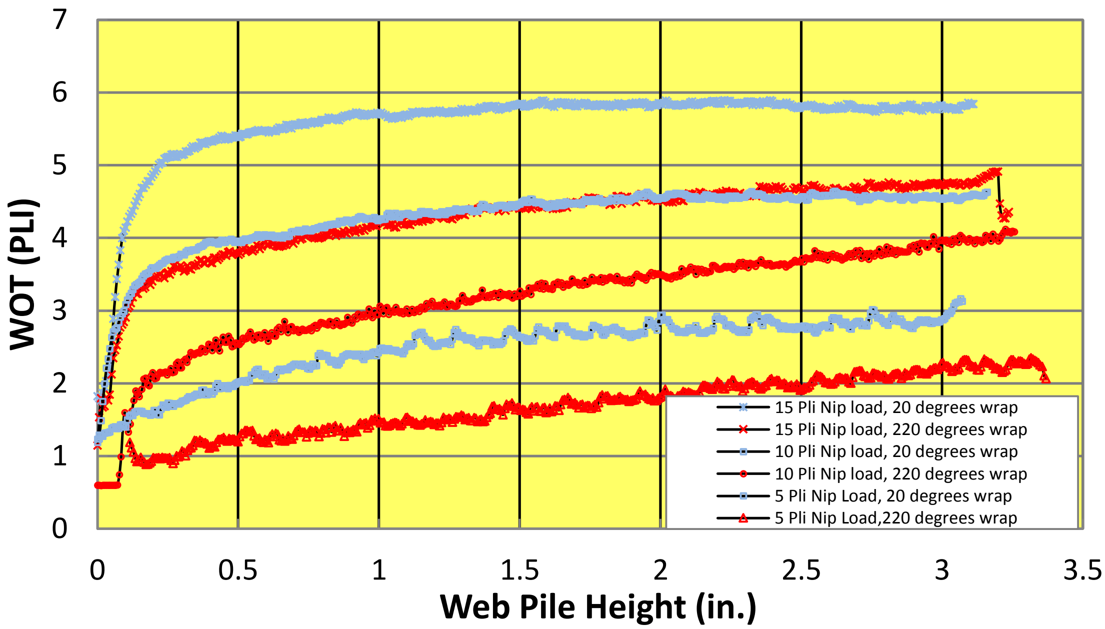

Figure 3-4 Comparison of WOT measurement for different wrap angles

In order to have a quantitative result, recorded WOT values were averaged and listed in Table 3-1 below. The results in this table indicate that the measured WOT value for the 20^{o} wrap angle are 30% to 40% greater than the measured WOT value for the 220^{o} wrap angle.

Table 3-1 WOT percentage difference between different wrap angles

Nip Load(Pli)	WOT_ave(Pli) 220^{o} Wrap Angle	WOT_ave(Pli) 20^{o} Wrap Angle	Difference%
5	1.658	2.554	42.53%
10	3.240	4.375	29.83%
15	4.335	5.721	27.55%

The reason for the difference can be explained by the change of friction force in wrapping area in figure 3-5.

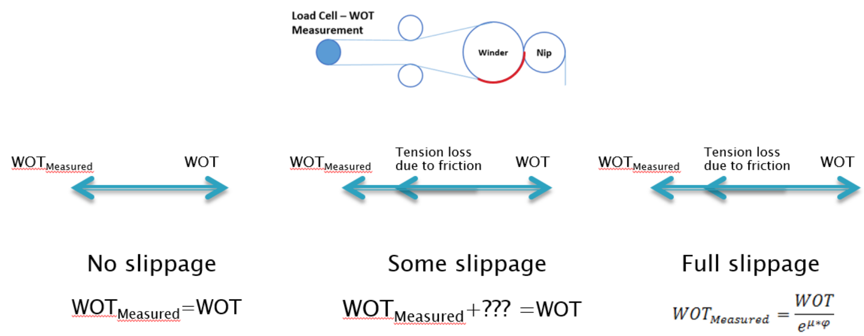

Figure 3-5 Web equilibrium within the arc of web wrap

In this wrap arc, slippage may or may not between the outer layer and the layer beneath. This slippage will induce friction forces which will lead to a loss of web tension (T_{loss}). So the measured WOT can be described by the real WOT value subtracting this T_{loss}. If no slippage occurs, then the measured WOT value would be the actual WOT when winding without the WOT measurement rollers. If slippage happens everywhere within this wrap arc, Good[22] gave the following expression to compensate for the loss of tension:

$$WOT_{measured} = \frac{WOT}{e^{\mu*\varphi}}$$

Where μ is the coefficient of friction between web layers

φ is the wrap angle

In most situations, the amount of slippage that occurs in the wrap arc is unknown. Thus the difference between the measured WOT and the actual WOT is unknown. If the arc of slip after the nip roller is less than the arc of wrap, then the Pfeiffer WOT measurement method would be a non-interfering method of measurement. If the arc of slip is equal to the arc of wrap, then the Pfeiffer method interferes with the WOT measured.

3.3.2 Impact of Winding Velocity

An experiment was designed to investigate the impact of winding velocity by winding the web at two different velocities: A constant angular velocity of 1r/s was the first case, and a constant linear velocity of 12.25 in/s was the second case. All other winding parameters and web material were as same as the experiment in last section.

During winding, computer recorded the winding parameters such as WOT every several micro-seconds. Thus data were stored in term of time. To have a plot for WOT versus web pile height, a calculation must be made to find out the web pile height at a certain time. When winding with a constant angular velocity, the web pile height can be calculated by simply multiplying the time with web thickness as shown in equation 3.1:

$$h(t) = 0.0048 * t \tag{3.1}$$

When winding with a constant linear velocity, assume the height of web wound on roll is h and number of layers of wound web is n, the total web length can be calculated by summing the diameter of all previous layers of web together. Meanwhile, this total web length can also be calculated by multiplying time and winding velocity. Then web pile height h can be calculated by solving the following equation:

$$\int_0^{\frac{h}{0.0048}} \left(\pi * (3.2 + n * 2 * 0.0048)\right) dn = 12.25 * t \tag{3.2}$$

After calculated the web pile height in terms of time with both winding cases, the measured value of WOT when winding for three different nip loads can be seen in figure 3-6.

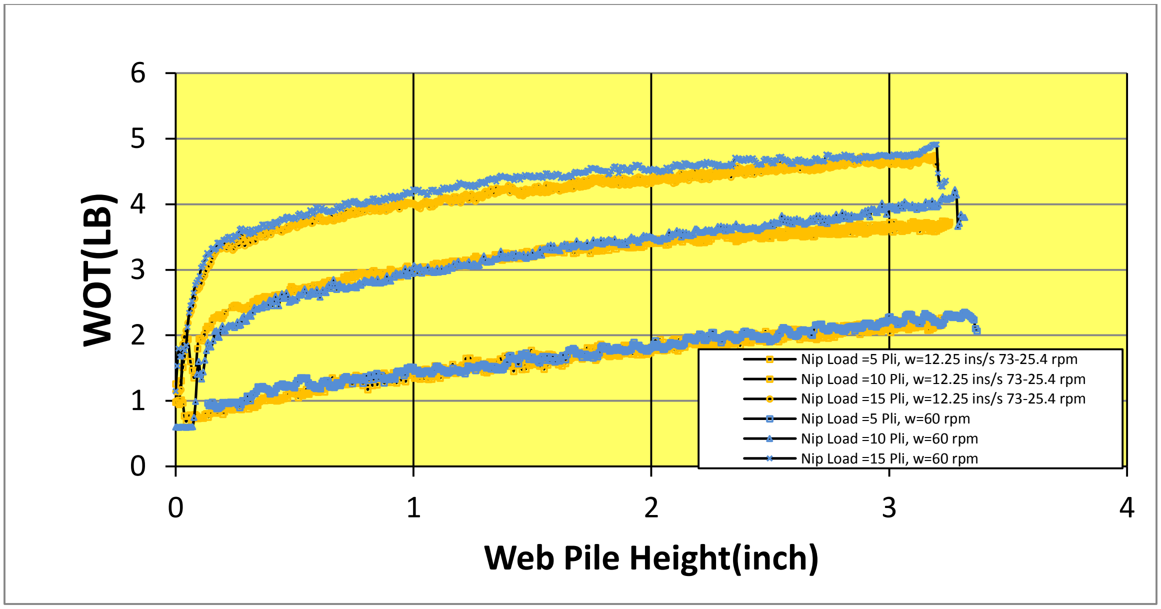

Figure 3-6 Comparison of measured WOT between different winding velocities

The results in this figure indicate that the measured WOT value for the constant linear velocity are very close to the measured WOT value for the constant angular velocity. In another word, the winding velocity doesn't interfere the measured WOT value.

3.3.3 Impact of Web Travel Distance

In this experiment the WOT measurement roller was moved to three different positions and the measured WOT was compared for equivalent web tensions and nip loads. The position of WOT measurement roller was defined as the distance between the center of this roller to the center of wind roll core. The winding process lasted 600 seconds for each test. The recorded data can be seen in figure 3-7 below.

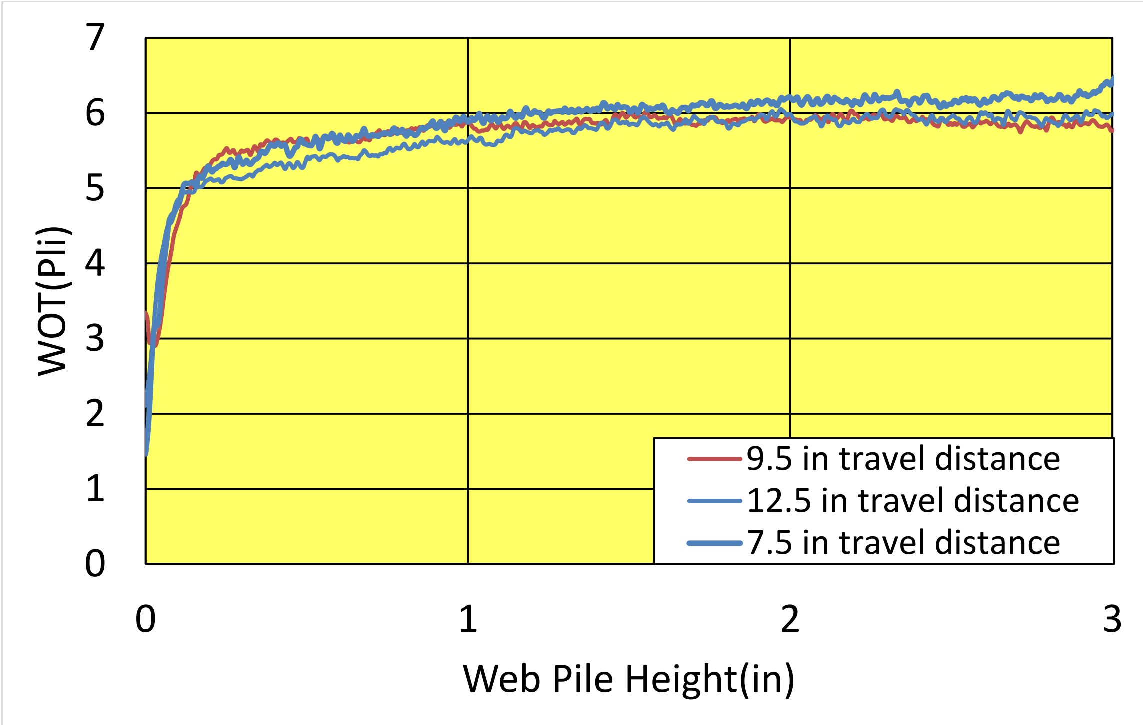

Figure 3-7 Comparison of measured WOT for different web travel distances

It appears the web travel distance has little or no effect on the measured WOT, Although this represents only the results of three tests, the wrap angle effects shown in figure 3-4 have much greater impact on measured WOT than web travel distance.

3.4 Conclusion for Pfeiffer's WOT Measurement Method

Based on the results of these experiments, a good understanding is gained of why Pfeiffer's WOT measurement is an interfering method. The main reason is that by extracting the web to make the WOT measurement that the friction forces between the outer layer and the layer beneath have been interfered with. These friction forces would have been different compared with the web have not been extracted to make the WOT measurement, and lead to the final value of the actual WOT.

The wrap angle test results shown in figure 3-4 show that when these friction forces are disturbed and can lead to WOT measurement results different.

Winding velocity test results shown in figure 3-6 and the web travel distance test results shown in figure 3-7 show that winding velocity and web travel distance have little effect on WOT measurement.

It is concluded that whatever WOT measurement method is used that the outer layer should not be extracted or disturbed to make the measurement.

CHAPTER IV

DEVELOPMENT OF A NON-INTERFERING WOT MEASUREMENT METHOD

4.1 Introduction

From chapter 3 it was found that any new method to measure or infer WOT should not disturb the friction forces beneath the outer layer. The outer layer should not be disturbed or extracted to make WOT measurements

4.1.1 Use of Pull Tabs and Winding Models to Infer WOT

Pressure sensors called “pull tab” are wound into the winding roll. After winding is complete, a hand-held force gage is used to determine what force was required to cause the pull tab to slip between web layers as shown in figure 4-1. With a known friction coefficient and the area of contact between the pull tab and the surrounding layers, a pressure can be inferred at the radial location of the tab. Often several pull tabs are inserted during winding at varied radius to establish how pressure varies with wound roll radius.

A winding model is then used. The radial modulus (E_r) is measured as a friction of pressure and Young’s modulus (E_θ) is measured. With known core properties of stiffness and outer radius, the web properties ($E_{r,}$ E_θ) and a known final wound roll radius, only one input is unknown: The tension in the outer layer (WOT). The WOT is varied in this method until the pressures measured by pull tabs match the pressures predicted by the model. When completed, the WOT is known.

Pull tabs disturb the wound roll as shown in Figure 4-1. To minimize the disturbance the thickness of the pull tabs should be comparable or smaller than the web thickness. Steel shim stock is often used for pull tabs that are 0.001 inches thick and 0.5 inches wide. If the pull tab can be longer than the wound roll is wide then the area of contact remains constant while the force measurement is made. Although pull tabs can be quite accurate there are limits to the maximum pressure they can measure. The desire to minimize the tab thickness to minimize the radial disturbance between layer results in this limitation on maximum pressure. Shim stock is high strength steel and wound rolls with internal pressures of 60-70 psi will result in the pull tab undergoing tensile failure prior to causing the slip that would allow pressure measurement. It was known that in fact the pressures in rolls of the web that would be wound would be greater than 70 psi and thus another method was proposed.

Figure 4-1 How a pull tab disturbs roll structure

4.1.2 Use of Core Pressure and Winding Models to Infer WOT

As discussed in the *literature survey*, Mollamahmutoglu created an axisymmetric winding model. This winding model can calculate the core pressure in wound roll by inputting necessary parameters. This code requires inout of web thickness across the web width, Young's modulus for the web in the r,θ,z directions (E_r,E_θ,E_z), core dimensions and material properties and the final wound roll radius. The WOT in the outer layer has more impact in roll stress and core pressure than any other input. If the WOT varied until the core pressures predicted by the model match those measured in tests, the WOT would be known. The flow chart for the implementation of this method is shown in figure 4-2.

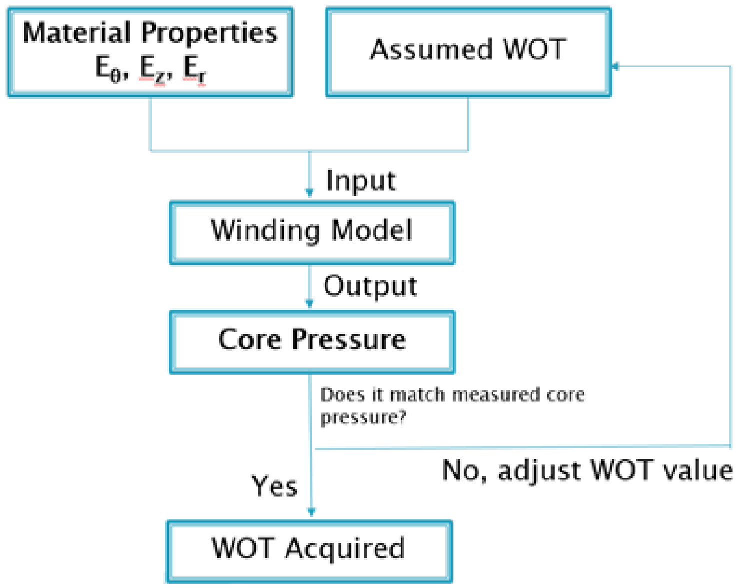

Figure 4-2 Flow chart for a non-interfering WOT measurement method

4.2 Core Pressure Measurement

The WOT measurement method proposed requires the ability to measure core pressure.

4.2.1 Experiment setup

The high speed winding machine in the Web Handling Research Center at Oklahoma State University was used to conduct the winding tests and to make the core pressure measurements. This winding machine is shown in figure 4-3 with a name list for all major components. The web unwinds and passes over several idler rollers and a web position guide. The web wraps a 10 inch diameter nip roller 180 degrees before winding onto diameter instrumented core. This instrumented core was composed of 25 sectors. Each one inch in width. Each sector is instrumented with strain gage wired into a full Wheatstone bridge. Calibration was achieved by subjecting this instrumented core to known pressures and then measuring the output of each Wheatstone bright. After roll of web material was wound the calibration could be used to determine the core pressure in each sector.

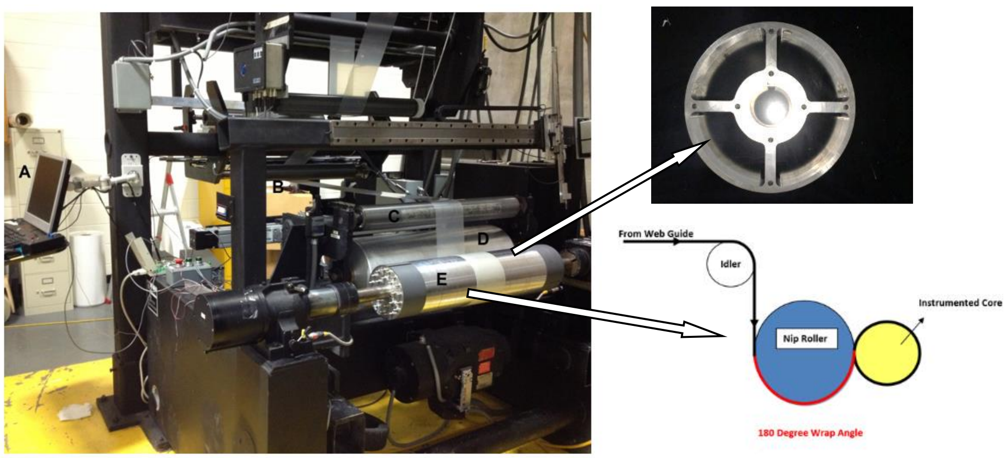

Figure 4-3 HSWL in OSU High Speed Winding Lab

A-LabVIEW Data acquisition system

B-Roller supported by load cells for measurement and control of web tension

C-Idler roller that controls nip roller web wrap

D-10 inches diameter nip roller with load cell

E-8 inch diameter instrumented core composed by 25 1-inch sectors.

Two kinds of nip rollers were used in these experiments, one was an aluminum roller 10 inches in diameter, and a second one had same 10 inch outer diameter but was covered with one inch thick layer of rubber (60 IRAD).

Center winding, surface winding and hybrid winding experiments were conducted under similar winder operating conditions except different nip load as shown in Table 4-1. The winding velocity is 50 fpm and the web tension was 3 pli. A 6 inch wide PET film was used in these experiments and 6 sectors of the instrumented core were used to measure the core pressure width wise. Web was wound onto the core until a 1.5 inch pile height was developed. Once the pile height reached 1.5 inches, the core pressure was recorded while the web tension was maintained. Each winding case was repeated three times and an average core pressure was established.

Table 4-1 List of experiment conditions

Nip Load with Nip roller Type	Center winding	Surface Winding	Hybrid Winding with 50% torque assist	Hybrid Winding with 100% torque assist
6 pli Nip Load	Yes(Al/Rubber)	No	NO	No
12 pli Nip Load	Yes(Al/Rubber)	No	Yes(Al)	Yes(Al)
25 pli Nip Load	Yes(Al/Rubber)	Yes(Al/Rubber)	Yes(Al)	Yes(Al)
33 pli Nip Load	Yes(Al/Rubber)	Yes(Al/Rubber)	Yes(Al)	Yes(Al)
45 pli Nip Load	Yes(Al/Rubber)	Yes(Al/Rubber)	Yes(Al)	Yes(Al)
62 pli Nip Load	Yes(Al/Rubber)	Yes(Al/Rubber)	Yes(Al)	Yes(Al)
72 pli Nip Load	Yes(Al/Rubber)	Yes(Al/Rubber)	No	No

WOT results calculated by this method are listed in Appendix A.

4.3 Material Properties

4.3.1 Material Constants

A 1000 gage(0.01 inch) PET (Polyethylene terephthalate) film with a density of 0.06 lb/in was chosen for this research. One reason for choosing this material is that the property of this material is almost time independent. Material properties must input to the winding model in this method. In this chapter in-plane modulus $E_{11}(E_\theta)$, $E_{33}(E_z)$ and out-of-plane modulus $E_{22}(E_r)$ as illustrated in Figure 4-4 are measured experimentally as well as the coefficient of friction of this web.

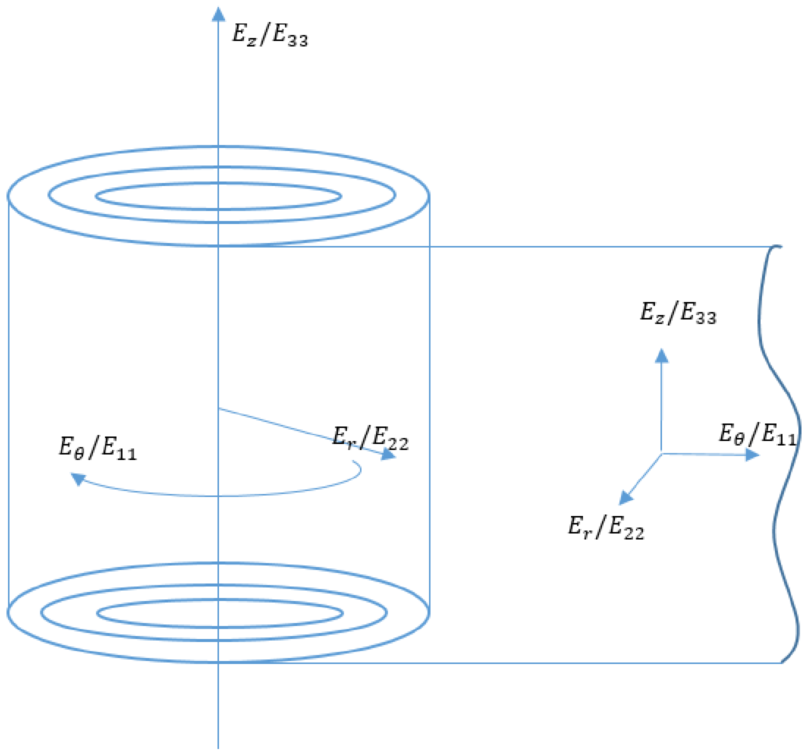

Figure 4-4 E_{11}, E_{33} and E_{22}

4.3.2 In-Plane Modulus

For most webs, the in-plane modulus is greater than out-of plane modulus. This film was measured using ASTM standard[24] for modulus. A stretch test is used often to measure the in-plane modulus which has none of the grip alignment errors associated with the short specimens defined in the standard. has been approved to be more representative than measurement using ASTM standards in the wound rolls. To perform this stretch test, a 50 ft long web sample was needed. Full constrain was applied at the one end of the web and a uniform tension was applied to the opposite end via a force as shown in figure 4-5

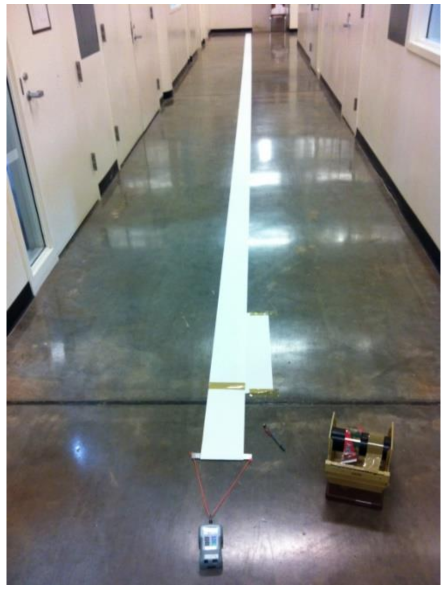

Figure 4-5 Stretch test

The results obtained from this method were very close to the company quotations. So company quotations were used instead of measured results in the winding model to calculate WOT. The company quotation for E_{11} is 710000 psi and E_{33} is 740000 psi.

4.3.3 Out-of-Plane Modulus

As discussed in *winding models,* web materials such as paper and PET film have a nonlinear compressive strain-stress behavior. Their compressive strain have an exponential relationship with compressive stress. The experiment to measure this relationship was to compress a stack of web with a continuously increasing load, and record the change of the thickness of the web of the stack on an Instron machine. With the recorded load versus stack deformation, the relationship between stress and strain could be determined. These measurements were conducted in an Instron 8502 servo hydraulic material testing system.

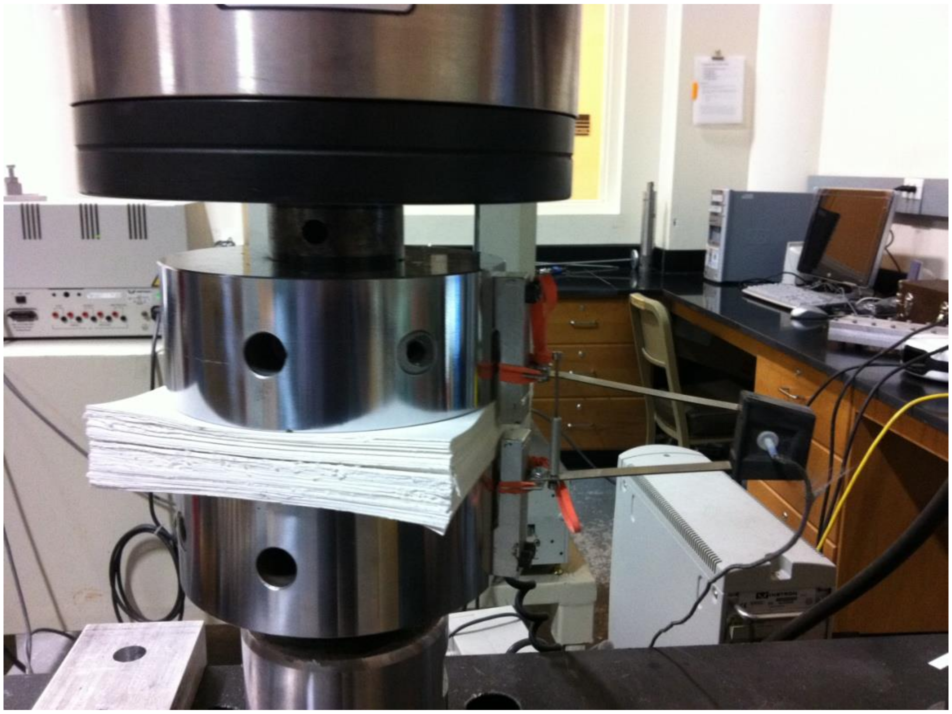

Figure 4-6 Apparatus used to measure out-of-plane modulus

Pfeiffer's [3,4] expression in equation 2.0 is used to describe this relation. The value of K1 and K2 can be obtained by using a least squared error routine. Then the out-of plane modulus can be described using equation 5.1.

$$E_r = K_2(K_1 + P) \tag{5.1}$$

However, because this modulus is pressure dependent, the best fit expression varies between different pressure ranges. To best describe this behavior, K_1 and $K_2$are calculated based on the pressure range and listed in Appendix A.

4.3.4 Coefficient of Friction

Though the coefficient of friction is not an input parameter for winding models when center winding, it is a very important parameter to calculate WOT using equation 2.13 as an empirical method.

Balaji conducted experiment to measure the kinetic coefficient of friction using ASTM standard[24] and obtained a result of 0.22. He stated that this value didn't agree with his winding model result. A flat testing bed which can simulate the winding environment was designed to measure the coefficient of friction as shown in figure 4-8.

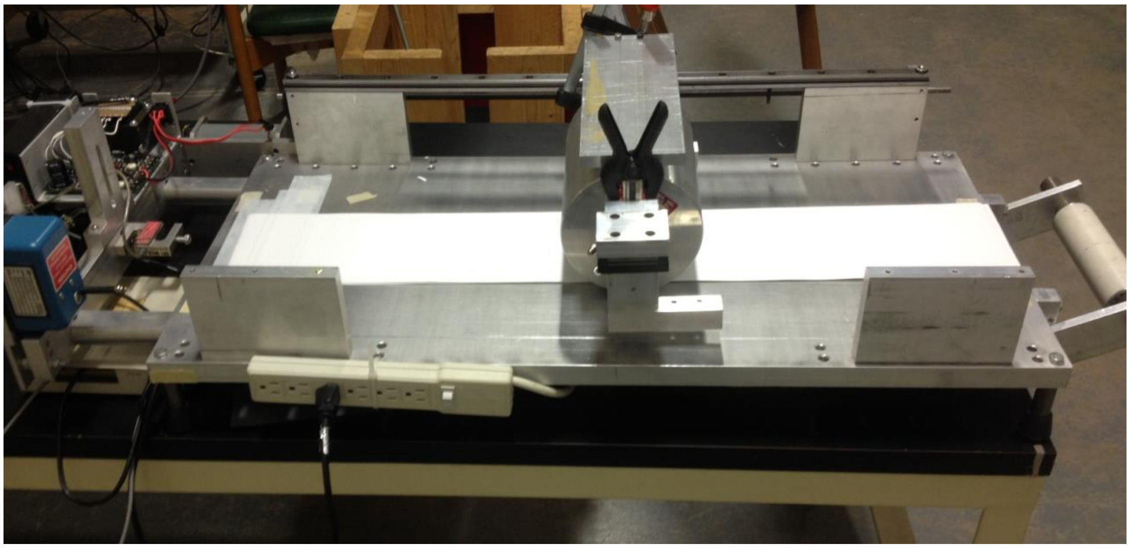

Figure 4-7 Flat test bed for coefficient of friction test

As shown in the figure, one layer of sample web is rested on a 10 sheet stack of web on a rigid base. The left end of this layer of web is connected to a load cell, and the right side of this layer of web is tightened to a known load which simulates the web tension. Two parallel horizontal linear rails are built on the base. A 4 inch diameter aluminum nip roller is assembled with two vertical linear rails which will allow dead weight added above the nip roller to be applied vertically to web. The nip roller is capable to travel horizontally in two directions along the rail. A linear potentiometer is used record the position while a motor is driven the nip roller from left side to right side.

As the nip roller rolls from its starting position, the tension exists in web and position of nip roller is recorded simultaneously. This behavior of the tension verses position is shown in Figure

4-9, and the coefficient of friction calculated using this method is 0.18. It is calculated by dividing the average nip-induced-tension by applied nip load.

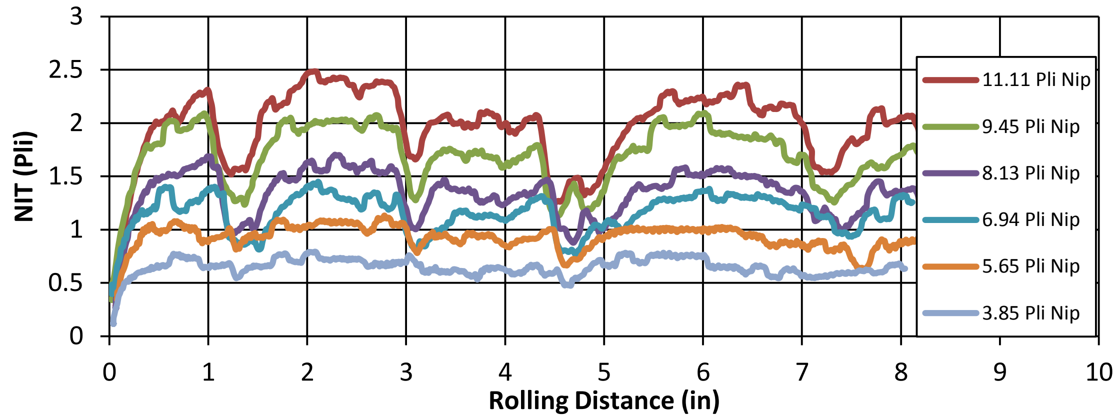

Figure 4-8 NIT vs Nip rolling distance

4.3.5 Web Thickness

The web thickness across the web width was found to vary. The winding model requires thickness to be input at the edge of each sector. Six one inch wide sectors were modeled which means seven thickness measurements were needed. These measurements are given in table 4-2.

Table 4-2 Web Thickness Variation

CMD Location(in)	0	1	2	3	4	5	6
Web Thickness(in)	0.0097	0.00977	0.0097	0.0097	0.00971	0.00968	0.00968

4.3.6 Core Stiffness

The core for the wound roll is modelled using axisymmetric finite elements similar to the elements used to model the web. The core must have the core inside radius, outside radius and material properties input. The core sectors are machined from isotropic aluminum. Its Young's modulus is E= 9.9 $*10^6$ psi, and its Poisson ratio is 0.33.

As mentioned previously, the outside diameter of this core is eight inches and thus the outside radius is four inches. The inside radius is 3.75 inches.

The web thickness across the web width was found to vary. The winding model requires thickness to be input at the edge of each sector. Six one inch wide sectors were modeled which means seven thickness measurements were needed. These measurements are given in table 4-2.

CHAPTER V

WOT RESULTS

5.1 Measured Core Pressure for All Winding Cases

The measured core pressures for all center winding, surface winding and hybrid winding cases are given in Appendix B. Also the core pressure for all winding cases where the rubber covered nip was used are shown.

5.2 WOT Results

Now the method for determining WOT using a winding model in combination with a core pressure measurement described in section 4.1.2 was applied. The properties from chapter 4 were input to the winding model and the WOT was varied until the core pressure in appendix B were best matched. The WOT estimated in this fashion are given in Appendix C. Note that each winding test was performed three times to establish repeatability. The average WOT and standard deviation for each winding case is presented in table 5-1.

Table 5-1 WOT for all winding cases with 6 pli web tension

Center winding with aluminum nip roller							
Nip load(pli)	6	12	25	33	45	62	72
WOT(pli)	4.4	5.2	6.9	7.85	9.6	11.1	12
Surface winding with aluminum nip roller							
Nip load(pli)			25	33	45	62	72
WOT(pli)			2.5	3	6	7.1	8
Hybrid winding with 50% Torque assist							
Nip load(pli)		12	25		45	62	
WOT(pli)		2.5	4.5		7.3	8.8	
Hybrid winding with 100% Torque assist							
Nip load(pli)		12	25		45	62	
WOT(pli)		4.95	6.55		9.25	10.8	
Center winding with rubber covered nip roller							
Nip load(pli)	6	12	25	33	45	62	72
WOT(pli)	5	6.47	8.7	9.75	11.75	12.85	13.5

These data are now presented in figure 5-1

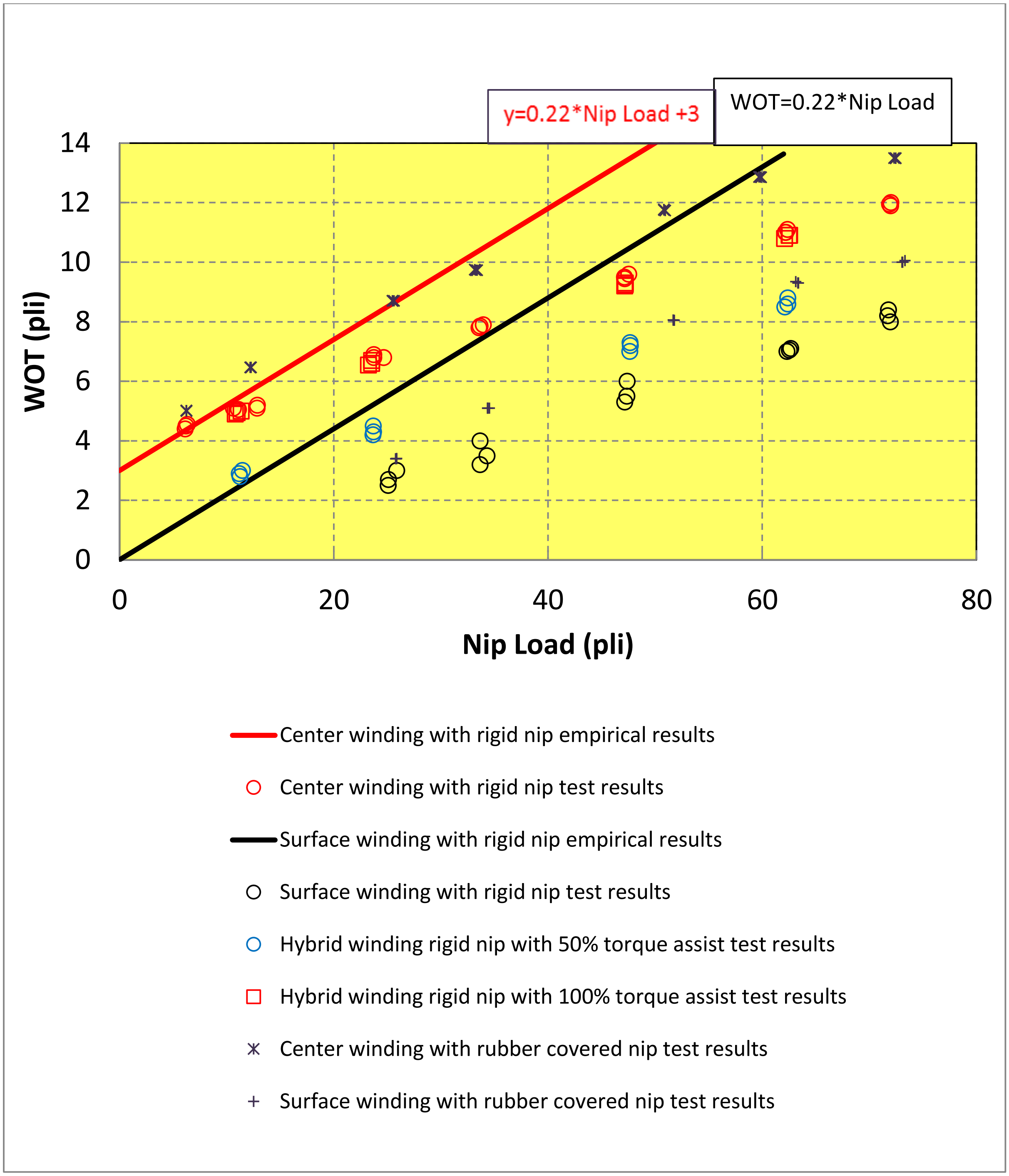

Figure 5-1 Inferred WOT

5.3 Discussion of Results

At low nip loads the inferred WOT values agree with the empirical expressions WOT=0.22*Nipload +3 (2.13) and WOT=0.22*Nip load (2.15) for center and surface winding. The 100% hybrid winding cases are setup as surface winding with added core torque. The added core torque is that which would be associated with center winding at the same nip load. The result should be that little or no torque should be required to maintain the surface nip at its test velocity. Note the average WOT for 100% hybrid winding is essentially that of center windings at the same nip load.

These results are consistent with other results presented in the literature survey that show at low nip load the slope of the WOT with respect to nip load is very close to the friction coefficient. At higher nip loads the slope decreases.

CHAPTER VI

ERROR ESTIMATION FOR NON-INTEFERING MEASUREMENT METHOD

A winding software code called MAXIWINDER which was developed by Mollamahmutoglu[26] is used to infer the WOT in this research. Material properties are important inputs for this winding model. Errors when measuring these parameters can propagate through winding model and cause the variation of final results. To evaluate this non-interfering WOT measurement method, it's necessary to find the possible error range for each parameter, and test the sensitivity of these parameters of the winding model.

5.1 Sensitivity of input WOT on Winding Model

As discussed in winding models, in the literature survey, WOT is the most influential parameter on the output internal pressure. The non-interfering method developed depends on how close the calculated core pressure can match measured core pressure, the sensitivity of this input WOT on winding model was necessary to be tested.

Two nip cases in center winding were chosen: 6 pli nip load and 72 pli nip load. The WOT obtained were 4.4 pli and 12 pli, respectively. However, if input a WOT increased by 4%, the change of core pressure were significant. These results can be seen in table 6-1 below:

Table 6-1 Sensitivity of input WOT on winding model

		Core pressure(psi) width wise					
WOT(pli)		1	2	3	4	5	6
12.0		328.754	273.112	252.379	237.524	213.104	228.552
12.5		366.874	308.072	285.851	269.734	242.532	258.570
	Differences%	10.96013	12.03051	12.43781	12.69936	12.91726	12.32478
4.4		95.544	80.089	61.415	52.005	43.769	39.411
4.7		105.549	88.153	68.704	58.705	49.570	45.238
		9.950708	9.586379	11.20294	12.10442	12.42985	13.76603

5.2 Sensitivity of Single Material Property on Winding Model

Two cases in center winding and two cases in surface winding were used here to evaluate the sensitivity of single material property on winding model. The minimum nip load and the maximum nip load cases were chosen. A ±5% variation of each moduli was used. The acquired WOT based on varied modulus were then compared with calculated WOT based on measured modulus.

First case. The calculation is based on a 5% error of E_θ, center winding with 6 pli and 72 pli nip load. $K_1$and K_2values are chosen as 0.01,325 and 0.01,265 respectively, E_z=740000 psi, the calculated core pressure are compared with averaged measured results. The percentage difference can be seen in Table 6-2.

Table 6-2 WOT Variance brought by 5% variance of E_θ during center winding

Sector Number	1	2	3	4	5	6		6pli
Measured Core pressure	107.18	86.80	60.32	50.08	50.23	46.72	WOT (psi)	Diff %
E_theta =710000	107.20	93.37	62.14	52.74	45.65	34.10	440	
E_theta =710000*1.05	107.15	92.98	61.22	51.77	44.75	33.32	450	2.25%
E_theta=710000* 0.95	106.53	93.04	62.39	53.10	46.00	34.45	430	2.30%
								72 pli
Measured Core	300.97	291.60	257.16	239.46	237.67	220.09	WOT	Diff %

pressure							(psi)	
E_theta =710000	299.73	290.62	238.16	222.94	209.50	176.29	1100	
E_theta =71000*1.05	300.23	290.21	236.25	220.59	206.77	173.28	1120	1.80%
E_theta=710000* 0.95	300.43	292.65	242.41	227.87	215.04	182.17	1075	2.30%

The results indicate that the variance of WOT brought by 5% variance of E_θ are less than 2.5%

A very similar calculation is ran to test how sensitive E_z is to winding model, The results can be seen in Table 6-3.

Table 6-3 WOT variance brought by 5% variance of Ez during center winding

Sector Number	1	2	3	4	5	6		6pli
Measured Core pressure	107.18	86.80	60.32	50.08	50.23	46.72	WOT (psi)	Diff %
E_z =740000	107.20	93.37	62.14	52.74	45.65	34.10	440	difference%
E_z =74000*1.05	107.38	93.376	62.109	52.710	45.631	34.069	440	0.00
E_z=740000*0.95	107.39	93.343	62.108	52.705	45.621	34.084	440	0.00
								72 pli
Measured Core pressure	300.97	291.60	257.16	239.46	237.67	220.09	WOT (psi)	difference%
E_z =740000	299.73	290.62	238.16	222.94	209.50	176.29	1100.	
E_z =74000*1.05	299.32	289.83	237.50	222.27	208.81	175.79	1098	0.18%
E_z=740000*0.95	301.07	292.04	239.33	224.14	210.73	177.26	1104	0.36%

The results indicated that the variance of WOT brought by 5% variance of E_z are less than 0.5%.

The last investigation is to find out how sensitive E_r was to winding model. As discussed before, E_r which could be represented by the value of K_2 had a variation range of ±5%. When winding with 6 pli nip load, K_2 value was chosen as 325.When winding with 72 pli nip load K_2value was chosen as 265. The value for other parameters were E_z=740000 psi, E_z=710000psi. The variation of WOT brought by 5% variance of E_r can be seen in Table 6-4 below:

Table 6-4 WOT variance brought by 5% variance of Er during center winding

Sector Number	1	2	3	4	5	6		6pli
Measured Core pressure	107.18	86.80	60.32	50.08	50.23	46.72	WOT (psi)	Diff %
K2=325	107.20	93.37	62.14	52.74	45.65	34.10	440	
K2=325*1.05	106.34	92.10	60.44	50.97	43.87	32.42	425	3.47%
K2=325*0.95	107.75	94.03	63.40	54.13	47.11	35.57	455	3.35%
								72 pli
Measured Core pressure	300.97	291.60	257.16	239.46	237.67	220.09	WOT (psi)	differen ce%
K2=265	299.73	290.62	238.16	222.94	209.50	176.29	1100	
K2=265*1.05	299.20	290.11	236.95	221.61	208.00	174.30	1080	1.83%
K2=265*0.95	299.80	290.49	238.70	223.62	210.37	177.58	1115	1.35%

These results indicated that the variation of WOT brought by 5% variance of material properties Er,E_θ and Ez separately were all less than 5% during center winding.

Similar calculation was done for surface winding cases to evaluate how WOT results varies when each material property changed. These results are listed in Table 5-4 below:

Table 6-5 WOT WOT variance brought by 5% variance of E_θ ,Ez and Er during surface winding

Surface winding with 25 Pli Nip Load			
Test of parameters	Eθ	Ez	Er
WOT(psi) with no variance	250	250	250
WOT(psi) with +5% for one parameter	255.000	249.000	242.000
difference%	1.9802	0.400802	3.252033
WOT(psi) with -5% for one parameter	242.000	251.000	259.000
difference%	3.25203	0.399202	3.536346
Surface winding with 72 Pli Nip Load			
Test of parameters	Eθ	Ez	Er
WOT(psi) with 0 error	800.000	800.000	800.000
WOT(psi) with +5% for one parameter	820.000	796.000	785.000
difference%	2.46914	0.501253	1.892744
WOT(psi) with -5% for one parameter	780.000	803.000	815.000
difference%	2.53165	0.374298	1.857585

These results indicated that the variation of WOT brought by 5% variance of material properties Er,E_θ and Ez separately were all less than 5% during surface winding.

5.3 Impact of combined material properties for winding

After investigate the sensitivity for each material property on WOT, Now we will see how much the WOT can vary if all the material modulus varied by 5%. Table 6-6 and table 6-7 listed the variance of WOT brought by 5% variations of all material modulus for center winding and surface winding. These results are then plotted in figure 6-1 and figure 6-2.

Table 6-6 WOT variance brought by 5% variation of all modulus during center winding

Nip Load (pli)	6	12	25	33	45	62	72
WOT variation% bring by +5% variation of input parameters	4.65	4.32	3.99	3.90	3.39	3.20	3.23
WOT variation% bring by -5% variation of input parameters	4.88	4.69	3.98	3.75	3.48	3.37	3.13

Table 6-7 WOT variation brings by 5% variation of all modulus during surface winding

Nip Load (pli)	25	33	45	62	72
WOT variation% bring by +5% variation of input parameters	4.08	3.39	3.05	3.15	3.17
WOT variation% bring by -5% variation of input parameters	3.92	3.28	3.28	3.05	3.08

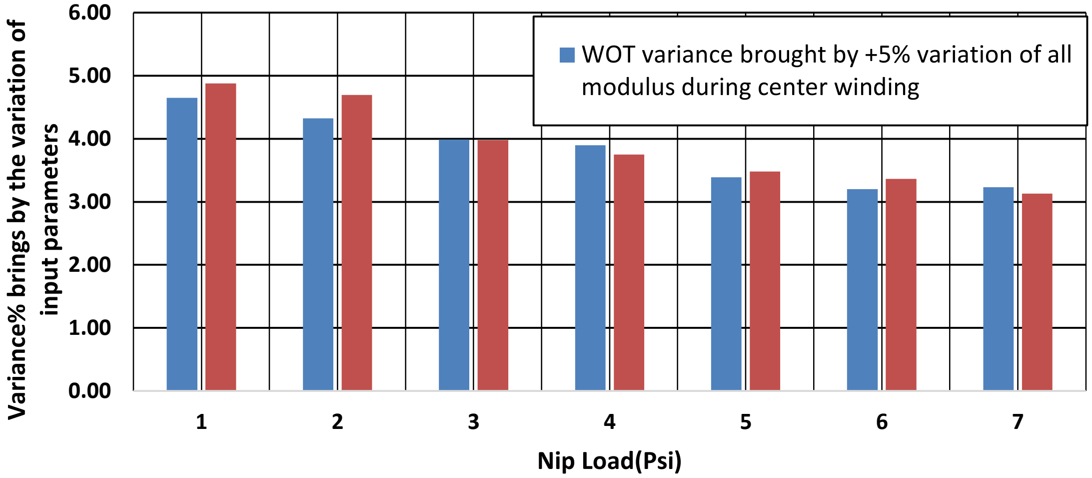

Figure 6-1 WOT variance brought by 5% variation of all modulus during center winding

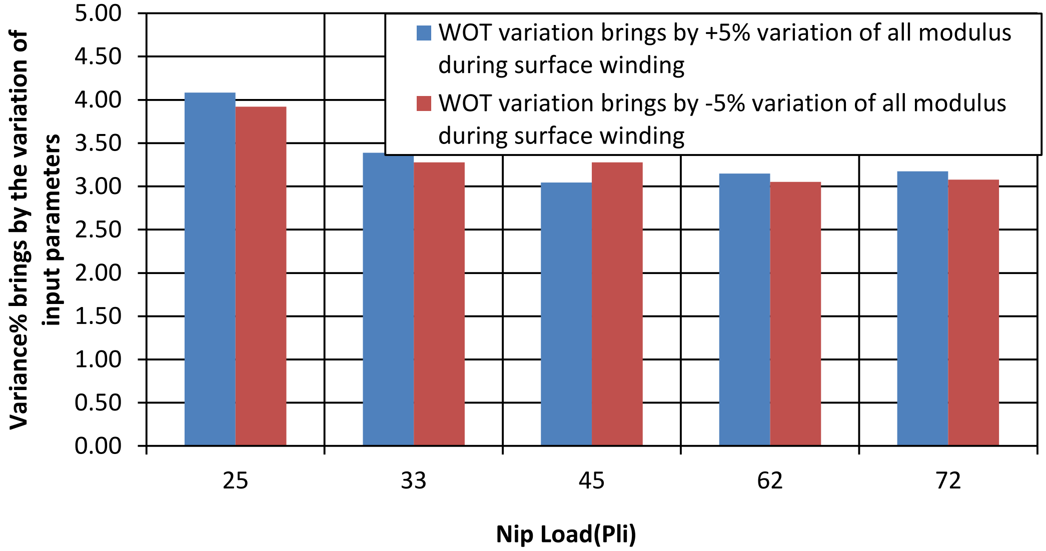

Figure 6-2 WOT variation brings by 5% variation of all modulus during surface winding

This study told us that the errors brought during material property measurement were normally with in a 5% range, and a 5% variance of the parameters had a small impact on the final WOT value.

Now it’s confident to say that a non-interfering WOT measurement method is successfully developed and evaluated.

CHAPTER VII

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

1, Pfeiffer’s interfering WOT measurement experiments were conducted. A better understanding was gained of why this method is a type of interfering method. Extraction of the web and the resulting wrap angle was proven to be the main reason cause of interference. Winding velocity and the length of web extracted to make the measurement did not affect the measured WOT.

2,A non-interfering WOT measurement method was developed. This method used a measured core pressure and winding model to infer the WOT. New method does not require extraction of the web and prevents interference. This measurement was easy to set up and operate.

3, The non-interfering WOT measurement method was proved to have a higher accuracy level when compared with the interfering method. The experiment results based on this method provided good agreement with empirical results.

6.2 Future Work

It is recommended that tests should be conducted to determine if this method works for more complex web materials such as nonwovens whose modulus are much lower that for PET films.

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APPENDICES

Appendix A

K$_1$ K$_2$ values for Pfeiffer's equation

0-80psi	Test 1	Test 2	Test 3	Average	Standard Diviation
k1	0.001326	0.001055	2.19E-05	0.000801	0.000688163
k2	329.9801	331.7349	364.0468	341.9206	19.18192836
Difference%	3.55424544	3.02400856	6.2683348		
0-110 psi				Average	
k1	0.001568	0.001153	2.15E-05	0.000914	0.000800435
k2	324.6067	328.9792	364.0468	339.2109	21.61934633
Difference%	4.40006411	3.0625117	7.0631008		
0-150psi				Average	
k1	0.002308	0.001813	6.26E-05	0.001395	0.001179742
k2	312.4023	315.0181	337.5133	321.6446	13.80482255
Difference%	2.91533639	2.08163601	4.8148403		
0-170psi				Average	
k1	0.002924	0.002295	9.08E-05	0.00177	0.001487793
k2	305.0102	307.7933	328.2963	313.6999	12.71718724
Difference%	2.80897306	1.90077703	4.547192		
0-230 psi				Average	
k1	0.00584	0.004744	0.00028	0.003621	0.002945112
k2	283.661	285.8902	300.6665	290.0726	9.24207232
Difference%	2.23504428	1.45231602	3.5866595		
0-300 psi				Average	
k1	0.012692	0.010588	0.00881	0.008054	0.00194328
k2	260.4614	262.2356	273.1695	265.2888	6.882269011
Difference%	1.83638542	1.15755783	2.9271347		
0-400 pis				Average	
k1	0.036859	0.030644	0.00383	0.023778	0.017552453
k2	229.4984	231.9119	238.8719	233.4274	4.867050519
Difference%	1.69746426	0.65135268	2.3055296		

Appendix B

Measured Core Pressure for All Winding Cases

Center winding with aluminum nip roller							
Sector Number	1	2	3	4	5	6	Nip Load (pli)
Pressure(psi)	104.25	85.59	59.42	49.20	49.68	46.96	6.33
	109.73	88.27	61.09	50.34	50.61	46.78	6.20
	107.58	86.55	60.46	50.71	50.42	46.41	6.12
	121.08	97.85	77.25	66.00	60.84	54.97	12.87
	123.63	100.15	79.34	68.26	62.33	56.43	12.83
	114.04	94.02	73.26	61.66	58.24	52.79	11.11
	165.13	141.17	116.26	101.09	97.68	85.39	24.66
	161.60	142.89	112.91	97.70	92.29	86.30	23.73
	161.60	142.70	112.91	97.32	92.84	86.11	23.75
	187.83	172.40	145.00	130.90	124.66	110.88	33.97
	192.73	177.39	144.37	129.39	124.29	115.43	33.57
	191.75	177.39	144.37	129.96	124.66	115.80	33.66
	231.87	217.06	189.27	173.92	171.00	151.49	47.53
	232.46	220.89	187.17	171.66	168.39	156.04	47.15
	233.05	220.70	187.59	171.47	167.09	155.86	47.16
	280.22	269.76	231.64	215.62	214.16	199.20	62.21
	273.37	264.58	227.23	211.47	210.07	195.93	62.37
	297.84	272.44	230.38	213.92	212.86	199.20	62.17
	284.32	258.91	241.66	239.84	217.78	239.55	72.00
	296.97	257.23	239.58	237.80	222.88	239.37	71.89
	293.52	255.34	237.13	235.38	219.60	236.86	72.00

Surface winding with aluminum nip roller							
Sector Number	1	2	3	4	5	6	Nip Load (pli)
Pressure(psi)	35.93	20.05	9.28	8.64	13.02	18.92	25.87
	35.93	19.28	9.28	9.20	14.14	17.09	25.08
	37.30	20.62	9.91	8.83	13.76	18.19	25.09
	61.38	39.79	27.95	23.73	22.88	26.75	34.31
	67.45	45.34	27.95	21.47	22.51	30.57	33.67
	66.86	44.39	26.48	22.03	23.25	29.66	33.66
	118.93	94.98	66.76	56.37	55.07	55.34	47.38
	118.73	95.36	66.97	56.00	55.26	56.61	47.38
	119.52	95.94	64.45	55.62	53.77	54.61	47.15
	165.13	145.38	109.34	95.43	90.80	89.21	62.53
	166.10	145.19	109.34	95.24	91.91	87.75	62.66
	167.47	146.72	111.23	96.37	92.47	88.66	62.30
	201.53	184.09	147.94	128.64	124.48	115.98	71.72
	195.27	177.39	143.53	124.49	119.08	109.42	71.80
	193.70	177.77	145.00	125.81	120.38	110.70	71.96

50% torque assist with aluminum nip roller							
Sector Number	1	2	3	4	5	6	Nip Load (pli)
Pressure(psi)	41.81	24.46	18.09	16.00	15.25	17.28	11.47
	44.35	25.03	16.41	14.86	14.69	17.64	11.18
	46.11	25.61	17.46	15.05	14.88	16.73	11.25
	91.92	71.79	52.07	43.92	40.93	39.13	23.67
	90.94	70.83	51.44	43.35	39.81	39.49	23.69
	94.07	71.79	52.07	43.73	40.93	39.13	23.72
	174.52	159.95	126.33	111.28	106.61	100.68	47.68
	178.24	162.44	129.06	113.17	109.41	100.87	47.67
	175.11	160.33	126.33	111.09	108.47	100.50	47.64
	221.50	209.01	172.27	157.13	155.18	144.57	62.38
	218.37	206.13	168.71	153.36	149.97	140.38	62.12
	217.39	205.17	168.50	151.09	149.60	137.65	62.39

100% torque assist with aluminum nip roller							
Sector Number	1	2	3	4	5	6	Nip Load (pli)
Pressure(psi)	112.47	91.53	75.78	63.17	62.14	55.16	11.35
	115.60	93.06	74.73	63.54	63.45	55.34	10.80
	114.43	92.68	74.31	63.35	61.03	52.97	10.98
	156.90	139.82	112.07	97.70	96.57	88.12	23.53
	158.08	140.40	112.91	97.70	96.57	88.48	23.53
	158.67	140.02	112.28	98.26	96.75	87.57	23.24
	225.81	211.31	177.73	161.66	156.67	144.57	47.22
	221.11	211.31	179.41	163.92	161.32	148.40	47.21
	222.48	212.84	180.24	164.30	161.51	148.40	47.16
	264.37	255.96	219.68	203.36	202.26	187.37	62.55
	261.24	254.43	219.05	202.98	203.74	187.55	62.09
	262.02	255.00	219.47	203.74	203.00	187.73	62.52

Center winding with rubber covered nip roller							
Sector Number	1	2	3	4	5	6	Nip Load (pli)
Pressure(psi)	127.15	97.85	72.63	60.90	59.17	53.15	6.25
	125.58	97.66	73.47	60.52	59.35	53.88	6.24
	126.37	99.00	72.42	60.52	59.35	54.61	6.26
	163.36	132.93	105.57	91.28	90.05	83.75	12.27
	164.93	134.27	106.61	92.22	90.98	83.75	12.26
	163.36	134.27	104.52	90.34	90.05	82.84	12.21
	225.81	202.49	174.16	158.45	154.06	142.02	25.47
	228.16	200.00	173.74	159.77	152.39	142.57	25.62
	227.57	200.96	175.21	162.22	152.02	141.29	25.51
	263.98	245.80	218.84	202.04	197.98	184.09	33.17
	258.89	250.02	215.91	203.55	199.09	181.18	33.26
	259.08	250.98	216.96	200.34	200.21	178.26	33.39
	311.54	296.59	271.29	254.49	254.73	236.36	50.82
	314.87	301.19	275.69	257.51	255.84	240.54	50.81
	313.89	299.85	272.75	259.02	253.05	232.53	50.94
	337.38	315.37	290.38	273.93	274.64	252.02	59.89
	339.34	316.33	291.84	273.17	275.20	254.38	59.80
	338.16	314.79	290.80	275.62	275.75	253.66	59.70
	351.28	338.17	315.13	297.89	299.01	275.87	72.31
	347.36	339.90	313.45	294.49	297.34	274.78	72.45
	349.52	341.62	315.97	291.47	301.62	274.23	72.45

Surface winding with rubber covered nip roller							
Sector Number	1	2	3	4	5	6	Nip Load (pli)
Pressure(psi)	75.08	49.37	32.35	24.67	26.60	30.57	25.88
	73.52	48.03	30.89	22.41	25.86	28.02	25.77
	73.71	48.99	31.94	22.79	25.67	27.66	25.84
	124.41	94.41	71.58	55.05	53.58	53.70	34.54
	124.02	94.79	71.79	56.00	54.33	54.43	34.36
	123.43	94.02	71.37	55.05	53.40	54.25	34.39
	211.91	184.86	159.27	136.56	131.73	128.18	51.80
	213.08	182.75	156.96	134.49	129.50	125.81	51.73
	215.24	183.14	156.33	136.38	130.62	127.45	51.70
	266.52	236.41	210.66	186.56	182.16	178.26	63.13
	257.32	234.69	210.03	185.24	180.48	176.26	63.38
	259.47	234.88	210.24	185.81	179.93	175.35	63.32
	296.27	276.66	252.83	228.08	224.21	216.14	73.33
	294.90	275.89	251.99	228.26	225.89	217.23	73.10
	295.69	277.04	251.78	227.13	224.58	216.32	73.05

Appendix C

WOT results obtained by new development non-interfering WOT measurement method

Center winding with rigid nip roller		
Nip Load (pli)	WOT(pli)	STDV
6.332297235	4.41	0.004714
6.200322709	4.4	
6.11523174	4.41	
12.86726841	5.2	0.012472
12.83073075	5.21	
11.11329	5.18	
24.66032534	6.9	0.014142
23.72572325	6.87	
23.7464534	6.87	
33.96506554	7.8	0.009428
33.57203329	7.82	
33.66430293	7.82	
47.52936667	9.55	0.02357
47.14779416	9.6	
47.16073835	9.6	
62.20916156	11.05	0.032998
62.37284265	11.02	
62.17260675	11.1	
72	12	0.02357
71.89288607	12.05	
72.00406964	12.05	

Surface winding with rigid nip roller		
Nip Load (pli)	WOT(pli)	STDV
25.87 25.08 25.09	2.50 2.50 2.50	0
34.31 33.67 33.66	3.00 3.05 3.05	0.02357
47.38 47.38 47.15	6.00 6.00 6.00	0
62.53 62.66 62.30	7.10 7.10 7.12	0.009428
71.72 71.80 71.96	8.10 8.02 8.00	0.043205

50% torque assist with rigid nip roller		
Nip Load (pli)	WOT(pli)	STDV
11.47 11.18 11.25	2.50 2.50 2.52	0.00942809
23.67 23.69 23.72	4.50 4.50 4.53	0.014142136
47.68 47.67 47.64	7.30 7.31 7.30	0.004714045
62.38 62.12 62.39	8.80 8.76 8.75	0.021602469

100% torque assist with rigid nip roller		
Nip Load (pli)	WOT(pli)	STDV
11.35 10.80 10.98	4.95 4.98 4.97	0.012472191
23.53 23.53 23.24	6.55 6.56 6.56	0.004714045
47.22 47.21 47.16	9.25 9.22 9.23	0.012472191
62.55 62.09 62.52	10.80 10.78 10.79	0.008164966

Center winding with rubber covered nip roller		
Nip Load (pli)	WOT(pli)	STDV
6.25 6.24 6.26	5.00 5.02 5.02	0.009428
12.27 12.26 12.21	6.47 6.47 6.47	0
25.47 25.62 25.51	8.70 8.70 8.70	0
33.17 33.26 33.39	9.75 9.73 9.73	0.009428
50.82 50.81 50.94	11.75 11.77 11.74	0.012472
59.89 59.80 59.70	12.85 12.86 12.86	0.004714
72.31 72.45 72.45	13.50 13.50 13.49	0.004714

Surface winding with rubber covered nip roller		
Nip Load (pli)	WOT(pli)	STDV
25.88 25.77 25.84	3.41 3.40 3.40	0.004714
34.54 34.36 34.39	5.10 5.10 5.10	0
51.80 51.73 51.70	8.05 8.05 8.06	0.004714
63.13 63.38 63.32	9.35 9.30 9.30	0.02357
73.33 73.10 73.05	10.05 10.00 10.00	0.02357

VITA

Wenxing Jiang

Candidate for the Degree of

Master of Science

Thesis: DEVELOPMENT OF NON-INTERFERING WOUND-ON-TENSION MEASUMENT METHOD

Major Field: Web Handling

Biographical:

Education:

Completed the requirements for the Master of Science mechanical engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2014.

Completed the requirements for the Bachelor of Science/Arts in mechanical and aerospace engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2012.