A NEW METHOD FOR MEASUREMENT OF WOUND-IN-TENSION IN WEBS WOUND INTO ROLLS

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ABSTRACT

The Wound-In-Tension (WIT) is the tension in the outermost layer of a winding roll. The Wound-In-Tension is an important parameter that controls the stresses inside the wound roll which in turn determines the quality of the wound roll. Existing on-line methods of measuring or inferring WIT can be interfering measurements or suffer from inaccuracy. This paper documents a method of on-line WIT measurement that is based on the change in deformation of the web from a first location upstream of the winder, where the web tension is known, to a second location where the web has become the outer layer of the winding roll. It will be shown that these measurements can be made by non-contacting means such as Laser Doppler Velocimetry or by contacting means where encoders are employed. Results of the WIT measurement by the new method are compared to traditional WIT measurements on wound rolls of various materials.

INTRODUCTION

A web is a material whose thickness dimension is extremely small compared to the width and length dimensions. Webs are only conveniently stored in the form of wound rolls. Webs are wound onto the outer surface of a winding roll with a tension that creates stresses in the wound roll that will give the finished roll some integrity for subsequent web processing operations. These stresses can also cause pressure, slippage, and buckling related defects. Thus knowledge of these stresses is important in determining the quality of a roll that awaits conversion for subsequent processing prior to final conversion to a consumer product [1].

The Wound-In-Tension (WIT) is the tension in the outermost layer of the winding roll. The inputs for a simple one-dimensional winding model such as that described by Hakiel [2] include: web tension, core stiffness, inner and outer radii of the roll, Young's in-plane modulus for the web, and the radial modulus of the web. If a sensitivity study is performed using a winding model, where the pressures and circumferential stresses output are studied for a fixed percentage change in each of the inputs, it will be found that altering the winding tension or WIT has greater impact on the internal stresses that are output than any other input. Thus the WIT is the most important factor in determining the stresses in a winding roll.

The magnitude of the WIT varies depending on the winder type and on web properties. The simplest case is that of a center winder. In this case, for webs that are not very compressible in the out-of-plane dimension, the WIT approaches the tension of the web in the winder tension zone [1]. For webs that are more compressible the WIT will be less than the web tension in the winder zone when center winding [3]. Many winders have a roller, called a nip or rider, impinged into the outer surface of the winding roll. The web may wrap the nip roll first or it may wrap the surface of the winding roll first. If torque is supplied only to the nip roller, the winder is called a surface winder. If torque is supplied only to the core of the winding roll, the winder is called a center winder with an undriven nip. In some cases torque is supplied to both the center of the winding roll and to the nip roller. Depending on the control strategies these winders have various names such as surface winders with center assist, differential torque winders, and center winders with surface (nip) assist. Multiple drum winders, the most common of which is the two drum winder, wind rolls between two large drums. Sometimes one of the two drums is replaced with a driven belt which is usually called a belted winder. Belted winders may rely totally on the belt to provide the torque required to wind the roll. Some examples of the winders discussed are shown in Figure 1. Some insight has been given regarding the levels of WIT provided by these winders that are more complex than the center winder.

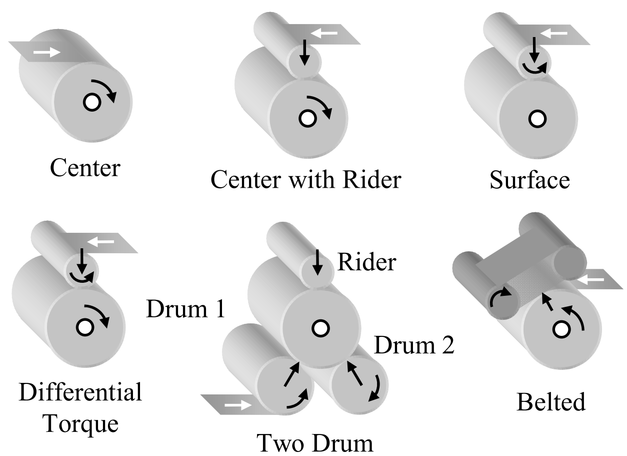

Figure 1 – Various Types of Winding Equipment (white arrows depict direction of web travel, black arrows depict nip loads, and curved arrows depict potential torque inputs).

Some simple WIT algorithms have been documented previously and have the forms:

$$\begin{aligned} WIT_{center\ winder} &= T_w h \\ WIT_{center\ winder\ with\ nip} &= T_w h + \mu_k N \\ WIT_{surface\ winder} &= \mu_k N \end{aligned} \qquad \{1\}$$

where WIT is the wound-in-tension (N/cm), T_w is the web tension (N/cm^2), μ_k is the kinetic coefficient of friction, N is the nip load (N/cm) and h is the web thickness (cm)

[1]. Unfortunately determining the WIT for a specific web being wound on a specific winder is not as easy as these expressions might lead one to believe.

The WIT can drop to values less than that predicted by expression {1} at higher levels of nip load when center winding with a nip. The nip load and friction coefficient combine to restrict the slippage in the nip contact zone. That slippage is necessary for the web tension to change from the tension upstream of the winder to the final value of WIT after the web has become the outer layer of a winding roll. Likewise when surface winding, web tension may begin to contribute to the WIT after this slippage becomes restricted and the WIT becomes larger than that shown in expression {1}. Computing the actual level of WIT for a given web on a given winder has been shown to be difficult but possible [4-6] and involves inputs that are difficult to determine.

There is need for on-line measurement of WIT. Very few on-line measurement techniques for any type of roll structure measurements have been developed. The two most successful on-line measurements have been the wound-in-density analyzer developed by Eriksson [7] and the WIT-WOT (wound-in-tension wound-off-tension) analyzer developed by Pfeiffer [8].

Of the two methods, Eriksson's method was most practical in the production sense since it required nothing mechanically different in the winder. Encoders were used to establish the velocity of the web at the winding nip and the angular velocity of the winding roll. With on-line measurement of web thickness the density analyzer was able to produce plots of roll density as a function of radius. The premise of this method was: If density profiles that corresponded to good quality rolls could be developed for a specific web then through closed loop control of the winder operating parameters one would attempt to maintain that density profile for all rolls wound of that web. One would then assume that all rolls with that density profile were rolls of good quality. In many cases the defects witnessed in wound rolls are not well defined in units of density. Pressure related defects are good examples in rolls of plastic film or coated papers. These webs have high K_2 factors (Pfeiffer's compressibility constant [9]) and small changes in roll density lead to large changes in roll pressure. The problem is that roll density cannot be measured on-line with the precision required to accurately deduce the pressure except in cases where the web is highly compressible (i.e. low K_2) [10].

Pfeiffer's WIT-WOT machine directly measured wound-in-tension and wound-off-tension. The outer layer of an unwinding roll was pulled away and directed over an idler roller mounted on load cells. This layer then was returned to the surface of the unwinding roll which it wrapped prior to exit of the unwind zone. If no losses occur due to slippage or the viscoelastic decay of stress in the unwinding roll one could determine what profile of WIT with radius must have existed when that roll was wound. This concept was novel in that many winders are not well instrumented and the profile of winding torques and nip loads and other important factors in determining the WIT may not be well known. By unwinding the wound roll and determining the wound-off-tension one could deduce what WIT must have been present when winding on the production winder. The WIT-WOT had a surface winder and thus was able to make WIT measurements for surface winding. A diagram of the WIT-WOT machine is shown in Figure 2.

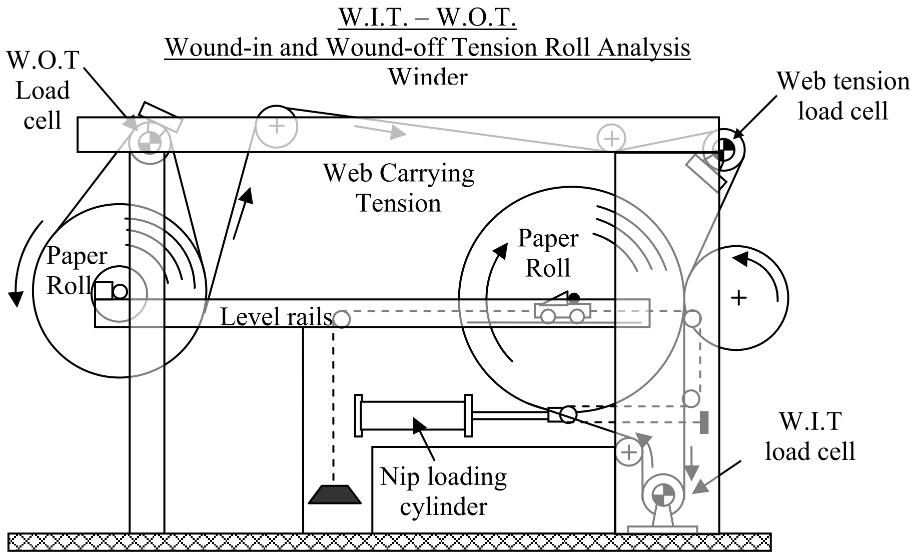

Figure 2 - Diagram of the WIT-WOT Analyzer developed by Pfeiffer

Thus experimental parametric studies were possible to develop WIT profiles with radius that would be associated with defect free rolls. Pfeiffer's method had the advantage that it measured the input that is most important in determining the internal stress and quality of the wound roll. Two problems that were associated with the method were that:

- Later research showed that slippage could occur between the outer layer and the wound roll that would affect the magnitude of the WIT that was measured. This slippage became possible as a result of extracting the outer layer to allow the WIT measurement. If it was known that the slippage was occurring the measurement could be corrected but the difficulty was knowing when slippage occurred [11].
- The method was not generally applicable on production winders where an additional idler on load cells and the change in thread path would be a nuisance during automated roll changes. Also many would be remiss to pull the outer layer away from the winding roll after they have landed it successfully on the winding roll in production.

This paper focuses on the development of a new method which exhibits the advantages of the wound-in-density method developed by Eriksson and the WIT method developed by Pfeiffer.

DEVELOPMENT OF A NEW METHOD FOR ON-LINE WIT MEASUREMENT

When winding with a nip roller impinged into the wound roll, the nip roller causes a change in machine direction strain in the web. The change in strain results in a change in the deformed length of the web. This change in length has to be accommodated in the winding process. Due to equilibrium, the velocity of the winding roll must either speed up or slow down to accommodate the change in length. . Thus the velocities upstream and downstream of the nip are different and are a direct measure of the strain that the web undergoes due to the nip. From conservation of mass, Shelton derived the following expression relating the strains and velocities in two successive web spans [12]:

$$(1-\varepsilon_2)V_2 = (1-\varepsilon_1)V_1 \qquad \{2\}$$

Solving this expression for the strain in the second span yields:

$$\varepsilon_2 = \frac{V_2 - V_1}{V_2} + \frac{V_1}{V_2}\varepsilon_1 \qquad \{3\}$$

The strain in the span downstream from the nip, which in this case is the outer layer of the winding roll, will be the WIT divided by the web thickness (h) and the web modulus (E_{MD} (N/cm^2)). The strain in the span upstream from the nip will be the web tension (T_w) divided by the web modulus. After substituting into expression {3} and solving for the WIT it is found:

$$WIT = \frac{T_W + \left(\frac{V_2 - V_1}{V_1}\right)E_{MD}}{V_2/V_1}h \approx \left[T_W + \left(\frac{V_2 - V_1}{V_1}\right)E_{MD}\right]h \qquad \{4\}$$

where V_2 is the surface velocity of the winding roll, V_1 is the surface velocity of the web upstream of the nip roller, and h is the web thickness. Expression {4} will yield the WIT in units of load per unit width of web (N/cm).

It is assumed that all the parameters in the right hand side of expression {4} can be measured. The web modulus and thickness would be measured in off-line tests and the web tension just upstream from the winder will be measured by passing the web over an idler roller supported on force transducers or by other means. Continuous means of monitoring the velocity of the web upstream of the nip (V_1) and the outer surface of the winding roll (V_2) are required. This can be accomplished without contact using Laser Doppler Velocimetry or by use of encoders when contact is possible.

The change or apparent change in the frequency of the wave motion owing to the relative motion of the source and the receiver is known as the Doppler shift. The same terminology is conventionally extended to the case wherein the frequency shift is produced by the movement of an intermediate inert object through which wave motion is transferred from the source to the receiver. This is the usual situation in laser Doppler measurements of velocity. Yeh and Cummins [13] were the first to demonstrate the technique of Doppler shift measurements using laser light in determining flow velocities. They measured the fluid flow velocity using the fringe patterns due to the shift of light scattered from tiny particles intentionally introduced and borne in the fluid flow. Lasers produce a very intense monochromatic light very suitable for this type of measurement. There are a number of variations of the technique, which may broadly be described as laser Doppler anemometry (LDA). Laser Doppler Anemometry (LDA) or Laser Doppler Velocimetry (LDV) is a single point optical measurement technique that enables the velocity of the seeded particles (~0.5 - 5 microns (in air) or 1~20 microns (in water)) conveyed by a fluid flow to be measured in a non-intrusive manner. Tsai and Wu [14] demonstrated the use of LDVs in measuring the velocity of a moving solid surface.

The schematic shown in Figure 3 displays the positions in which the LDVs or the encoders (E) can be placed to measure the required velocities V_2 and V_1. For a given web the effect of winder operating variables such as winding tension and the nip load on the WIT can be studied for surface and center winding cases. Note that LDV_U or E_U is the measure of the velocity of the web upstream of the nip roller (V_1) and LDV_D or E_D is the measure of the downstream surface velocity of the winding roll (V_2).

Although the methodology of the measurement system appears simple, the accuracy of the WIT measured based on velocity measurement depends on the accuracy of the LDVs and encoders. Commercial LDVs are available which provide velocity measurements with an accuracy of ±0.1% and with repeatability of ±0.05% or less. In expression {4} the change in strain between two points 1 and 2 is $(V_2-V_1)/V_1$. Assume there is no strain or velocity change but that there is error in the measurement of the velocities that will produce an apparent strain. In the worst case the velocity at position 2 could be read 0.1% too high and the velocity at position 1 could be read 0.1% too low. This would produce an apparent strain of (1.001V-0.999V)/(0.999V) or 0.2%. This apparent strain is not related to stress in the web, but it will produce a stress and hence a WIT error. The error in WIT will depend on the magnitude of the modulus of elasticity. For the example of a fine coated paper whose properties are given in Table 1, the error in WIT would be:

$$WIT_{error} = E_{MD}\varepsilon_{apparent}h = 6271MPa * 0.002 * 79.38\mu m * \frac{1m}{100cm} = 9.95\frac{N}{cm} \qquad \{5\}$$

An error term of this magnitude is unacceptable. Thus it would appear that the inference of WIT from expression {4} based upon velocity measurements acquired simultaneously at points 1 and 2 would result in failure, except for the case of very low modulus webs. Most LDVs produce a quadrature pulse output proportional to the length of the material that passes through the measurement site in a given period of time. This length measurement is produced by integrating the measured velocities with respect to time. The LDVs used in this research output 1000 TTL (Transistor Transistor Logic) quadrature pulses for every 0.305 meters (1 foot) of web material that passed through the measurement site[1]. Thus instead of measuring instantaneous velocities, a counter/timer board would be triggered and pulses from both LDVs would be counted until the LDV at station U produced 100,000 pulses. The difference in pulses between stations D and U divided by the pulses counted at station U is a direct measurement of the change in strain between the two station measurement points. Expression {4} can be rewritten in terms of pulses counted through a fixed period of time or until a target number of pulses is attained at one of the measurement sites.

$$WIT = \left[T_W + \left(\frac{TTL\_Pulses_D - TTL\_Pulses_U}{TTL\_Pulses_U}\right)E_{MD}\right]h \qquad \{6\}$$

In the form given, expression {6} is suitable for reduction of pulse data to measurements of WIT where the pulse data may be received from either LDVs or encoders. Measurements with encoders incorporate measurement error as well. To reduce these errors the encoders must be driven with lightly loaded wheels. The part of the wheel that is in contact with the web should have a high friction coefficient. The encoders cannot be driven by nip rollers or winding drums. These rollers are responsible

[1] TSI Incorporated, LaserSpeed Model LS200, St. Paul, MN. Currently these devices are produced by Beta LaserMike, Dayton, OH

for making the WIT differ from the web tension T_w initially and the velocity of the surface of the nip roller is not necessarily the final velocity of the outer layer of the winding roll. The wheels that drive the encoders must be lightly loaded such that they do not produce slippage between the outer layers of the roll that would interfere with the level of the WIT. Winding rolls often have some eccentricity and so keeping a lightly loaded encoder wheel in contact with the roll may prove challenging, especially at high winding speeds. The encoders used in this research output 2048 pulses per revolution[2]. The encoder wheels were 8.89 cm (3.5 inch) in diameter which would yield 2235 TTL pulses for every 0.305 meters (1 foot) of web which passes the measurement site. This is roughly twice the number of pulses output by the LDV sensors. The LDV sensors do not work well on transparent webs whose surfaces are nearly optically flat. To make WIT measurements using LDVs on transparent webs with low surface roughness will require at least temporary opaque coatings with some roughness. When this is not possible other means such as encoders will be necessary to make the length measurements. The LDV measurements are preferable since they are made without contacting the web or winding roll.

The error associated with inferring the WIT from TTL pulses from either LDVs or encoders can be estimated from expression {6}. The maximum error would result when the first device outputs one pulse too high while the second device outputs one pulse too low. The WIT error can be estimated as:

$$WIT_{error} = E_{MD}\varepsilon_{apparent}h = 6271MPa * \frac{2}{100,000} * 79.38\mu m * \frac{1m}{100cm} = 0.1\frac{N}{cm} \qquad \{7\}$$

Thus the error in WIT decreases as the reference number of pulses (i.e. 100,000 pulses in {7}) increases. Another reason for recording the TTL pulses in relation to the length of the web rather than recording the web velocity data is the amount of data provided per unit web length. The velocity data output by the LDVs used in this research was updated every 8 mS resulting in 7500 measurements of velocity in a one minute time interval. The quadrature pulses are updated in real time. For a web traveling 15 m/min in a web line 49,200 pulses would be output in one minute. If the web velocity increased a proportionate increase in the number of pulses output would result.

The experimental setup is shown in Figure 3 with the exception of the data acquisition. The data acquisition was identical for the acquisition of the pulses from the LDVs and the encoders. The acquisition consisted of a National Instruments 6602 counter/timer board which was connected to a PC and controlled by a LABVIEW® VI. When triggered the counter/timer board would clear and begin counting pulses until one of the two channels reached 100,000 pulses. The counter would then trigger off and the total counts on each channel would be stored in file. The total counts from the two channels could then be reduced to WIT using expression {6}. It should be noted that the LDV measuring the surface velocity of the winding roll was mounted on a movable sled as shown in Figure 3. This was necessary because the LDV employed had a required focal distance of 0.305 m (1 ft). Since the outer radius of the wound roll increases during the wind the sled position and the LDV were slowly backed away from the winder shaft in closed loop control during experiments. The tension in the free web is measured by a load cell (LC) whose signal is used in closed loop control of the web tension by adjusting the current delivered to a magnetic hysteretic brake on the unwinding roll (UWR). The

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[2] Gurley Precision Instruments, Model 925 encoders, Troy, NY

® LABVIEW is a trademark of National Instruments.

nip roller (NR) and the nip loading cylinders (NLC) retract on a sled during winding to maintain 180^{o} of web wrap about the nip roller. This allowed the winder operating parameters of web tension and nip load to be independent of one another.

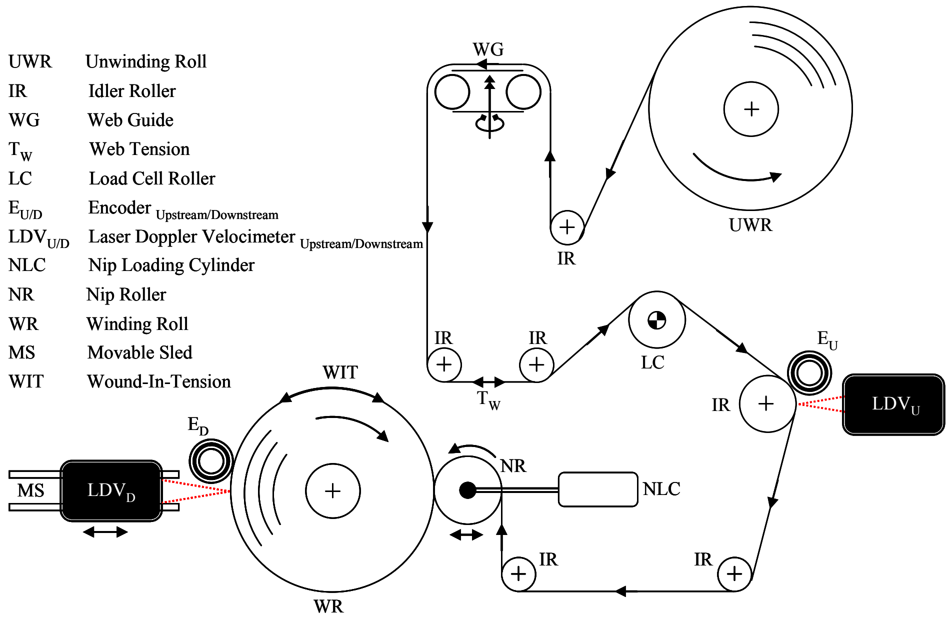

Figure 3: A schematic of the WIT measurement system that uses LDVs and encoders

For the sake of comparison, measurements were also taken by the traditional load cell method of WIT measurement. In Figure 4 a schematic of the winder shown previously in Figure 3 is shown, but with modifications in setup to make WIT measurements using the load cell method. The winder shown in Figures 3 and 4 has been used for previous WIT studies [11] and the winder can be setup as a surface winder or as a center winder with an undriven nip.

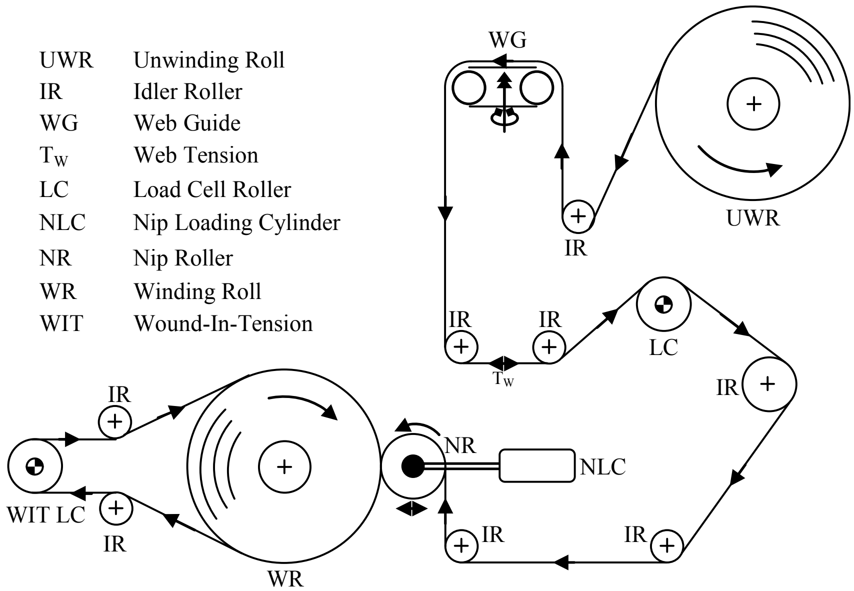

Figure 4 - A schematic of WIT measurement system using the load cell method

A picture of the winder setup for LDV measurement of WIT is shown in Figure 5.

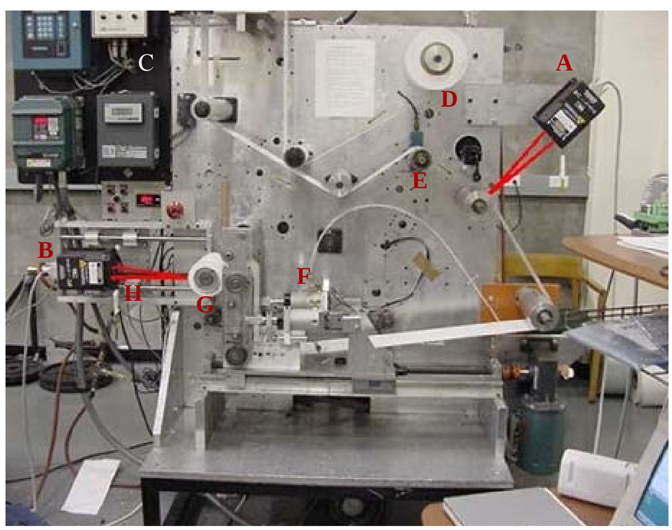

Figure 5 - Experimental set up for WIT measurement in wound rolls using LDVs (A-Upstream LDV, B- Downstream LDV, C-Control Panel, D-Unwind roll, E-Tension load cell, F-Nip cylinders, G-Wind up roll, H-Movable sled)

RESULTS AND DISCUSSION

The difference in quadrature pulse counts between the two LDVs is shown in Figure 6a for an example case. In this case the data was collected during center winding Fine

Coated (FC) paper 15.24 cm wide at different nip loads and at a constant web tension of 1.75 N/cm. Each data point represents the difference in pulse counts between the two LDVs after 100,000 counts have been collected at the reference LDV. Approximately 30.48 meters (100 ft) of web has been wound onto the roll during that period. It should be noted that the results of two winding tests are shown for each winding condition to demonstrate the fine repeatability of the measurement. Note that the difference in pulses counted at the two locations increases with increase in nip load which is indicating that the strain and the WIT is increasing with nip load which is consistent with the simple WIT algorithm for center winding with a nip shown in expression {1}. The strain in the web is expressed as the ratio of the difference in counts between the upstream and downstream location to the 100,000 counts counted at the upstream location. The WIT calculated from expression {6} using the data from Figure 6a is shown in Figure 6b. This WIT data is compared to the WIT measurements made using the load cell method in the same figure. Except at the highest nip load, the agreement between the two methods is excellent in center winding. WIT measured using the load cell method in surface wound rolls of FC paper is also shown in the same figure. The difference between the WIT values in center and surface wound rolls was found to be equivalent to the winding tension which had previously been observed by Good et al. [11]. This difference is also evident in the WIT expressions {1}.

The average of the difference between the WIT determined using the load cell method and the WIT determined using the LDVs and expression {6} is 0.22 N/cm (0.12 pli) for the data shown in Figure 6b. This average encompasses the data taken at a nip load of 9.73 N/cm, where the agreement is worst and where in fact the load cell method may be an interfering measurement. The error estimated in expression {7} is very comparable to the average difference between the WIT data acquired using the LDV and the load cell method. The average difference is affected by the instrumentation errors involved as well as any differences in winder operating parameters which may have occurred within the tolerance of the closed loop control systems used to control web tension and nip load. Thus the estimate of instrumentation error given in expression {7} appears reasonable.

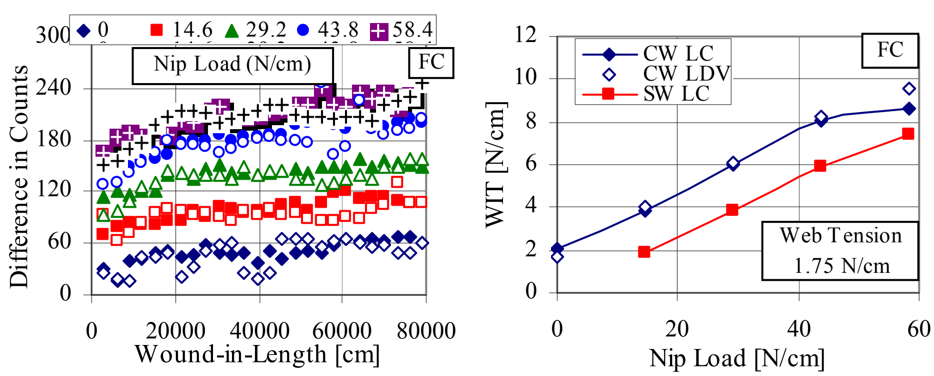

Figure 6 - (a) Difference in pulse counts as a function of wound-in-length at different nip loads in center wound rolls of FC paper, the filled and unfilled data points are indications of repeatability in first versus second tests and (b) WIT computed from (a) as a function of nip load

The WIT inferred from expression {6} based on LDV measurements in both center and surface wound rolls of MFC paper is shown in Figure 7a at different nip loads. The material properties of all the webs tested are given in Table 1. Although, the slope of the WIT data measured using LDV method in center winding differs from WIT data measured using the load cell method, the disagreement is only striking at the zero and the highest nip load level. In surface winding the agreement is excellent. The WIT data for different nip loads measured using both the LDV and the load cell methods in surface wound rolls of Super Calendared (SC) paper is shown in Figure 7b. Again the agreement is good.

Material	MD Modulus [MPa]	Web Caliper [µm]
Polyester (PET)	4137	53.34
Fine Coated Paper (FC)	6271	79.38
Machine Finished Coated Paper (MFC)	5723	71.12
Super Calendared Paper (SC)	7901	44.45
Newsprint	4027	71.12
22 gsm Polypropylene Spunbond Nonwoven	55.1	127

Table 1: Machine direction modulus and web thickness for different materials

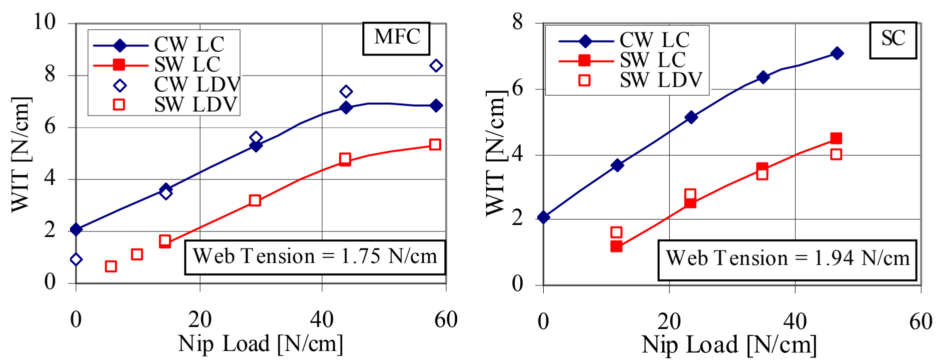

Figure 7 - (a) A comparison of WIT data in center and surface wound rolls of MFC paper using both LDV and LC methods (b) WIT behavior in center and surface wound rolls of SC paper

WIT data inferred from measurements using encoders and LDVs for center and surface winding polyester film is compared with the WIT data measured using the load cell method in Figure 8a. During the initial tests it was not apparent whether the LDVs could be used given the transparency of the PET film. Hence encoders were also used for the WIT measurements. This particular polyester had titanium dioxide particulates added during extrusion which provided adequate opacity and roughness for the LDV measurements. It is apparent the results shown in Figure 8a that the PET film had adequate opacity and surface roughness for the LDVs to function correctly. The agreement with the load cell method was good except at the lowest nip load. Air entrainment can be a typical problem in center wound rolls of PET when no nip roller is employed in the winding process and could be the cause for the disagreement in WIT data measured using LDVs at the lowest nip load. Note that the WIT inferred from expression {6} provided nearly the same result regardless of whether the measurements were made using LDVs or encoders for the zero nip load case. When air is wound into a roll of plastic film the tension in the outer layer can decay to values less than the web tension due to compression of the roll surface beneath the outer layer [3]. Note that the load cell method is yielding a value slightly higher than that expected from expression {1} for center winding (i.e. 1.75 N/cm). The air entrainment is entirely different for the load cell case and removing the web from the outer surface of the roll to make the load cell WIT measurement prevents the tension from decaying as it would have had the outer layer been in contact with the surface of the winding roll. When papers are coated they are also subject to entrained air. Thus it appears air entrainment may also explain the deviation between the load cell and LDV measurements of WIT for center winding the MFC paper at zero nip load (i.e. the nip roller is retracted) in Figure 7a. This behavior was noted only for the two impermeable MFC and PET webs.

In the case of newsprint WIT data was collected using the LDVs, the encoders, and the load cells in surface wound rolls. It was noted during experiments with newsprint that dust particles from the web that may have been due to slitting were airborne collected on the optical window on the front of the LDVs through which the transmitted and received laser light must pass. This could have been responsible for some error in the LDV measurements observed in Figure 8b. It also may either dictate that dust should be suppressed in the areas where LDV measurements are made or that LDVs with self cleaning optical windows be employed. This is an option offered by manufacturers of LDVs. During the center winding experiments only the load cell method was used to collect WIT data.

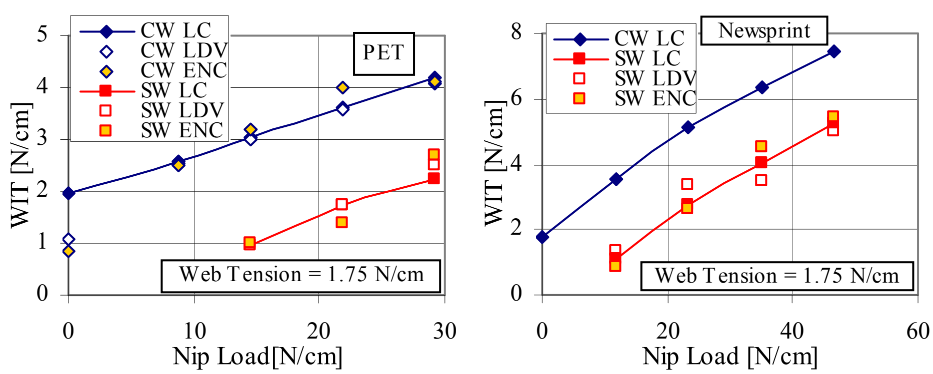

Figure 8 - (a) Behavior of WIT measured using LC, LDV and Encoder methods in center and surface wound rolls of PET (b) WIT behavior in center and surface wound rolls of Newsprint measured using LC, LDV and encoder methods

Finally results are shown for a 22 gsm spunbond nonwoven polypropylene web in Figure 9. These results are interesting for two reasons. First, it was unknown if the LDV measurements would be possible for webs in which the fiber density can be apparent to the unaided eye. The results show that measurements on nonwovens are possible. Second, note that at zero nip load that all measurement methods are yielding less than half of the web tension value of 0.876 N/cm which demonstrate the large loss of web tension from WIT that can result for webs such as this with a Pfeiffer K_2 compressibility on the order of 13 [3].

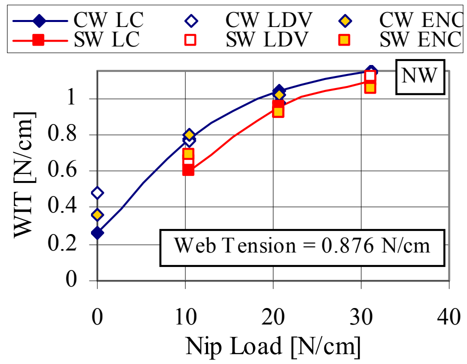

Figure 9 - WIT Data for a 22 gsm Spunbond Nonwoven collected using the Load Cell, LDV and Encoder means of measurement.

It is often difficult to define web thickness and thus modulus for light weight nonwovens. In these cases it may be more convenient to define expression {6} in the following form:

$$WIT = \frac{T}{W} + \frac{\left(TTL\_Pulses_D - TTL\_Pulses_U\right)}{NPUL} K \qquad \{8\}$$

In this expression T is the total web tension (N), W is the web width (cm), $NPUL$ is the number of pulses output by the LDV or encoder for a given length of web passage (pulses/cm) and K is the MD stiffness of the web between the upstream and downstream sensor ((N/cm)/cm) and thus WIT has units of N/cm. In this form, the method could be used to determine the change in tension in a web line between any two measurement sites given that the web stiffness is constant. The total tension at the downstream sensor is known if the tension (T) upstream of the upstream sensor is known.

CONCLUSIONS

A new method of WIT measurement has been demonstrated that relies upon the knowledge of the web tension upstream of the winder and then the measurement of the change in the deformed length of the web between that upstream location and a point on the outer layer of the winding roll. It has been shown to work in various types of webs. For all the webs tested, the agreement within the different methods of WIT measurement in both center and surface winding condition was good. The method offered is unique in that it allows measurement of WIT without removing the outer layer of the winding roll and the web encounters no additional idler rollers in the winder. It is superior to wound-in-density measurements since the method offers measurement of WIT. Knowledge of the WIT is preferable because when input with roll geometry, web and core properties to a wound roll model internal roll stresses can be predicted and used to quantify roll defects. While use of the LDVs is preferable (since they are non-contact) it has been shown that other sensors (in this case encoders) can be used to measure the change in web length when LDV measurements are not possible. The method has been shown to successfully work on center winders, center winders with rider or lay-on rollers, and surface winders. This method can be applied to any winder type.

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A New Method for Measurement of Wound-in-Tension in Webs Wound into Rolls

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Name & Affiliation	Question
Dave Roisum, Finishing Technologies, Inc.	I'm a little concerned about the LDV's living in an industrial environment. I am more interested in the encoder technique. You can't use the drums of the rider rolls because they are going to be interacting to the measurement in ways we don't want. Are you envisioning a lightly loaded footage wheel or something like that or a very lightly loaded contact roll? How would you do that in the field?
Name & Affiliation	**Answer**
J. K. Good, Oklahoma State University	First of all you should not be concerned with LDV's operating in harsh environments; their ruggedness has been demonstrated in the steel industry. In the steel industries there are LDV's focused on hot stretched steel a foot away. The LDV's have limit settings on them, so after a user defined length of web passes the measurement site a digital output switches to a TTL high and can be used to fire the cutoff hardware. The LDV is very useful in this mode in that it ensures the customer receives a precise length of web. Here you are a foot away from a web that is really hot in a bad environment, there's oil being slung off of this web and all sorts of things. LDV's can be purchased with self-cleaning windows on them to make them practical in the industrial environment that might not be so clean. In response to what you said about the encoder rolls, yes they have to be lightly loaded. If they are lightly loaded you have to worry about their dynamics ensure they remain in contact with the winding roll.
Name & Affiliation	**Question**
Kee Shin, Konkuk University	Expression 2 was derived assuming steady state conditions where accelerations would not affect strains. Could you use this method to measure the dynamic tension, too?
Name & Affiliation	**Answer**
J. K. Good, Oklahoma State University	In situations in which the mass and the accelerations of the web and the rollers are affecting the web strain and tension this method would be in error. The LDVs that were being employed in these experiments are capable of providing an updated velocity output every 8 mS. If you were trying to use individual velocity measurements that could vary as much as .1% to infer the strain from expression 2 those strains could error significantly. If however you count the TTL pulses that are

output in proportion to length these errors can be greatly diminished providing enough web is allowed to pass the measurement site before the strain or tension is inferred from an equation such as expression 6. Usually in winding the wound-in-tension changes slowly as the result of constant or gradual changes in nip load, the tension in the winder tension zone and wound roll radius. The measurements reported herein were based on approximately 100 feet of web being allowed to pass the LDVs.

The benefit of the measurement method being described herein is that it allows the measurement of a web tension in the web line in a location where it is difficult or interfering to use traditional methods of web tension measurement. If dynamic web tension variation through time is your concern you can employ the LDVs to make non-contact velocity measurements but you would have to use those measurements in conjunction with a dynamic model of the web and the rollers which contact it for you to infer the web strain or tension. In these cases an idler mounted on load cells might be preferable as long as the dynamics of the web and roller measurement system are well understood.

Name & Affiliation	**Question**
B. Sieber, Brückner Maschinenbau GmbH & Co. KG	What is the range of speed you measured?
Name & Affiliation	**Answer**
J. K. Good, Oklahoma State University	In these tests, we were probably never running over 30-40 meters per minute. The Laser Doppler Velocimeters are capable of producing the TTL pulses proportional to the length up to about 40 kHz. There is really not a web speed limitation when using the LDVs as we have described.