CONTAINERBOARD AND PRINTING PAPER WOUND-ON-STRAIN MEASUREMENTS ON A PILOT WINDER

By

Marko Jorkama and Pekka Palo
Valmet Technologies Inc.
FINLAND

ABSTRACT

Wound-On-Strain (WOS) measurement arrangement was set up on a single drum pilot-winder in the Winding Research Center of Valmet Technologies Inc. in Finland. The measurement was implemented with two Laser Doppler Velocimeters (LDV) – one measuring the paper web speed at the roll surface in the unwind stand or wind up and the other from the free web between the unwind and wind up. The target was to assess the feasibility of these roll structure related measurements. The measurement set up where one LDV is in the unwind enables also the WOS measurement of rolls produced with other winders while the set up where the LDV is in the wind up is convenient for the winding parameter trials. Comparison of these two measurements should provide valuable information of the viscoelastic properties of the wound roll.

The measurement set up will be presented in detail. The source and corrections of several error terms are discussed. WOS curves for containerboard rolls run with our customer's two-drum winder week earlier are presented. The influence of the web tension and nip load on WOS was studied. The influence of the nip load become clearly visible in the WOS while as in surface winding the changes in the tension did not become detectable in the WOS measurement. The measurement of several containerboard rolls wound in identical conditions resulted in very similar WOS curves. The WOS estimates obtained with the LDV measurement and with a Cameron Gap test were compared.

NOMENCLATURE

d	roll diameter	[m]
d_0	roll diameter at time 0	[m]
d_t	roll diameter at time t	[m]
f	roll rotation frequency	[Hz]
h	paper web thickness	[m]
L_r	web length average through the thickness of the web	[m]
L_a	web length measurement of the roll LDV	[m]

L_{sen} correction term of the web length measurement [m]
L_w web length measurement in the free span [m]
WOS Wound-On-Strain, i.e., the web strain of the outer layer [m]
WOT Wound-On-Tension, the web tension of the outer layer [N/m]
ε_r WOS
ε_w web strain in the free span
$\Delta\varepsilon$ $\varepsilon_r - \varepsilon_w$

INTRODUCTION

When the winding configuration is such that there is a nip roller in contact with the winding roll the calculation or measurement of the web tension entering into the winding roll becomes challenging [1 - 4]. The motivation for this study was to explore if and how two LDVs could be utilized in the measurement of the web strain in winding. This subject has been studied extensively at OSU's Web Handling Research Center (WHRC) by Dr. J.K Good and his research team [5]. Their conclusion was that LDVs are useful to produce fairly accurate estimates for the Wound-On-Tension in winding when certain measurement set up and data acquisition conditions are fulfilled. In this study we wanted to confirm their results for full scale winder used in the paper industry and also study the possibility to measure the previously wound roll structure when it is unwound on our pilot winder. Similar kind of technique was discussed by Pfeiffer [6, 7]. Instead of LDVs he used tension measurement of the web pulled temporarily out from the unwind roll.

Figure 1 shows the schematic side view of the measurement set up of our pilot winder. The first LDV is measuring the surface speed of the unwind roll, the second web speed of the free span between two guide rolls and the third is set up to measure the surface speed of the wind up roll. For the LDV's 1 and 3 there is arrangement to move the LDV's radially to keep the focal distance constant. We have two Laser BetaMike's 9000-303 LDVs available with 30 cm optimal focal distance. In our tests the LVD 2 in Figure 1 was always in the same position but other was at either at the position of LVD 1 or at the position of LDV 3.

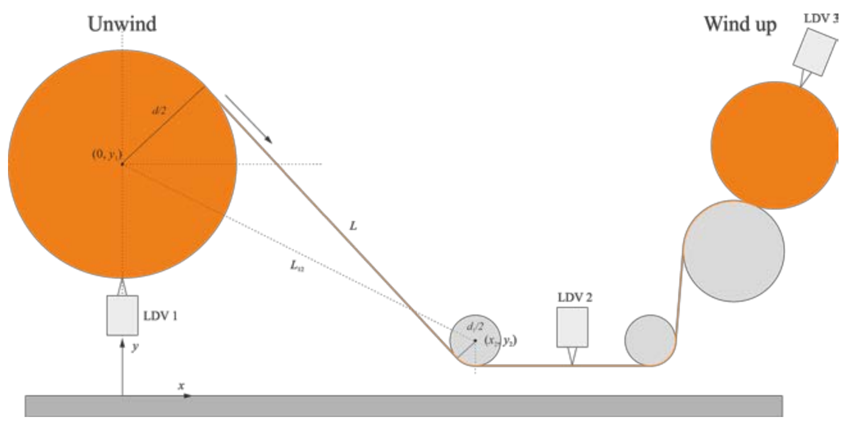

Figure 1 – Schematic side view of the measurement set up

Calculation of the strain difference

We used Laser BetaMike's Multitrak software to measure the LDV velocity and speed signals through RS-232 gates.

Let's consider first the length calculation form the unwind roll. The rate of growth of the roll diameter *d* and the roll rotation frequency *f* are connected as (decreasing roll)

$$\dot{d} = -2hf \qquad \{1\}$$

where *h* is the paper thickness.

The roll surface speed v_a and the average speed of the topmost paper layer through the thickness of the paper v_r are connected by

$$v_r = v_a - \frac{h}{d} v_a. \qquad \{2\}$$

Applying Eqs. {1} and {2} we get for the amount of paper passed through the sensor beam between time instances 0 ja *t* :

$$L_r = \int_0^t v_r dt = \int_0^t v_a dt - \int_0^t \frac{h}{d} v_a dt = L_a + \frac{\pi}{2} \int_{d_0}^{d_t} \frac{d+h}{d} dd = L_a + \frac{\pi}{2}\left(d_t - d_0 + h \ln \frac{d_t}{d_0}\right) \quad \{3\}$$

The last logarithm term is much smaller than the other terms and can hence be neglected. Above d_0 is the unwind diameter at time 0 and d_t is the unwind diameter at time *t*.

Also the web path length from the two LDVs is changing during the measurement. This is corrected by adding to the length term of Eq. {3} the change on the web path length between the sensors between the initial situation at time 0 and time *t*:

$$L_{sen} = L_{12}(\cos\alpha_0 - \cos\alpha_t) + \frac{\pi}{2}(d_0 - d_t) + \frac{\gamma}{2}(d_0 - d_t) + \frac{1}{2}(d_0\alpha_0 - d_t\alpha_t) + \frac{d_1}{2}(\alpha_0 - \alpha_t) \{4\}$$

Hence, the corrected length measurement of the unwind becomes

$$L_{rcor} = L_r + L_{sen}, \qquad \{5\}$$

i.e.

$$L_{rcor} = L_a + L_{12}(\cos\alpha_0 - \cos\alpha_t) + \frac{\gamma}{2}(d_0 - d_t) + \frac{1}{2}(d_0\alpha_0 - d_t\alpha_t) + \frac{d_1}{2}(\alpha_0 - \alpha_t) \qquad \{6\}$$

Above geometry terms are

$$L_{12} = \sqrt{x_2^2 + (y_2 - y_1)^2}$$

$$\sin\alpha = \frac{d + d_1}{2L_{12}}$$

$$\tan\gamma = \frac{y_1 - y_2}{x_2}$$

For the wind up the situation is simpler. Now the roll grows and we have

$$\dot{d} = 2hf \qquad \{7\}$$

For the observed length between time instants 0 ja *t* we get:

$$L_r = \int_0^t v_r dt = \int_0^t v_a dt - \int_0^t \frac{h}{d} v_a dt = L_a - \frac{\pi}{2}\int_{d_0}^{d_t} \frac{d+h}{d} dd = L_a - \frac{\pi}{2}\left(d_t - d_0 + h \ln \frac{d_t}{d_0}\right) \quad \{8\}$$

The correction term due to the change of the path length is very similar but of the opposite sign. The final corrected length becomes:

$$L_{rcor} = L_a - \frac{\pi}{2}\left(d_t - d_0 + h \ln \frac{d_t}{d_0}\right) + \frac{\pi}{2}(d_t - d_0) = L_a - \frac{\pi}{2} h \ln \frac{d_t}{d_0} \approx L_a \qquad \{9\}$$

Hence, in the wind up no correction is needed.

The Wound-On-Strain is defined as the strain of the outermost layer of the web at location on the circumference where the web in not sliding relative to the layer below it. The LDV measurement locations 1 and 3 are selected so that it can be assumed that the total strain is WOS at the measurement position. In unwind and wind up measurement set ups the WOS or ε_r is calculated as

$$\text{WOS}=\varepsilon_r = \varepsilon_w + (\varepsilon_r - \varepsilon_w) = \varepsilon_w + \Delta\varepsilon \qquad \{10\}$$

where ε_w is the total web movement direction strain at location 2 and Δε the strain difference between the roll surface and web. In the unwind measurement the strain difference between time instants t_1 and t_2 ($>t_1$) is calculated by

$$\Delta\varepsilon = \frac{\Delta L_{rcor} - \Delta L_w}{\Delta L_w}, \qquad \{11\}$$

where

$$\Delta L_{rcor} = L_{rcor}(t_2) - L_{rcor}(t_1) \qquad \{12\}$$

and

$$\Delta L_w = L_w(t_2) - L_w(t_1) \qquad \{13\}$$

above L_w is the total amount of web passed through the LDV 2 location.

In the wind up measurement the strain difference is calculated as

$$\Delta\varepsilon = \frac{\Delta L_r - \Delta L_w}{\Delta L_w} \qquad \{14\}$$

LDV alignment error on circular surface

When the LDV is not perpendicular to the web in the direction where the web is moving, the LDV is measuring smaller velocity than the actual. Figure 2 shows the alignment error schematic when measuring the roll surface speed. The alignment error is α, the distance of the LDV from the roll surface *a*, *r* the roll diameter, β the central angle and γ the angle between the laser beam and roll tangent. The central angle β and the angle of incidence γ can be calculated in terms of the other parameters and the results are presented in Eqs. {15, 16}. The relative speed measurement error due to the alignment error 1 – cos(γ) is calculated for several roll diameters and alignment angle error α values in Table 1. If the alignment error is more than 1 degree the results become unreliable for all applicable roll diameters. On the other hand if the error is less than 0.5 degrees then the speed measurement error is tolerable down to 0.5 m roll diameter. We estimated from mechanical measurements and from the shape of the unwind speed curve that in our case the alignment error was about 0.5 degrees.

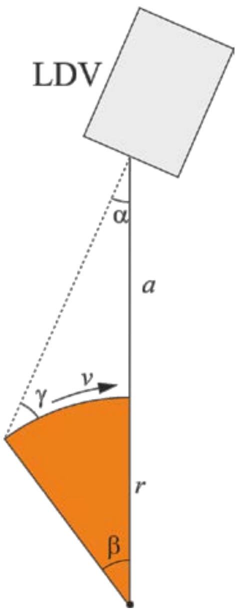

Figure 2 – Alignment error geometry when measuring the roll or roller surface speed

$$\beta = \cos^{-1}\left[\frac{r(a+r)\sin^2\alpha + \cot\alpha\sqrt{r^4\cos^2\alpha\sin^2\alpha - ar^2(a+2r)\sin^4\alpha}}{r^2}\right] \quad \{15\}$$

$$\gamma = \frac{\pi}{2} - \beta - \alpha \quad \{16\}$$

Error angle		Speed error %				
α [Deg]	Flat	d=1.4 m	d=1 m	d=0.5 m	d=0.25 m	d=0.1 m
0	0.000 %	0.000 %	0.000 %	0.000 %	0.000 %	0.000 %
0.25	0.001 %	0.002 %	0.002 %	0.005 %	0.011 %	0.047 %
0.5	0.004 %	0.008 %	0.010 %	0.018 %	0.044 %	0.187 %
0.75	0.009 %	0.017 %	0.022 %	0.041 %	0.099 %	0.421 %
1	0.015 %	0.031 %	0.039 %	0.074 %	0.176 %	0.749 %
2	0.061 %	0.124 %	0.156 %	0.295 %	0.706 %	3.030 %
3	0.137 %	0.280 %	0.351 %	0.665 %	1.596 %	6.952 %
4	0.244 %	0.498 %	0.625 %	1.185 %	2.853 %	12.732 %
5	0.381 %	0.778 %	0.977 %	1.855 %	4.491 %	20.767 %

Table 1 – Relative speed measurement error due to the alignment error in the direction of the movement of the web for various roll diameters

RESULTS

Wound-on-Strain measurement of 4 fluting rolls

German customer had sent us 4 70 g/m^2 fluting rolls, which were run about week earlier with their two-drum winder. The rolls were the rolls 3 and 4 (from the tending side to the drive side) from two 4 roll sets. The diameter of the rolls were 1450 mm, width 2500 mm and density about 750 kg/m^3. Their winder is equipped with two drums of diameter 1150 mm. The drums are coated with a thin layer of tungsten carbide for durability and traction. The resulting nip loads are shown in Figure 3. The rolls were wound at speed 2650 m/min.

When the roll diameter is small and the roll weight is small the nip loads are mostly due to the rider roll load. Towards the end of the set the roll weight becomes the dominant part. The two-drum drum winder is Valmet Windrum XL Pro, where the rear drum moves horizontally 340 mm apart from the front drum in the diameter range 100 – 700 mm. Because of the movement of the rear drum the rider roll load is not symmetrically distributed on the rear and front drum nips and, hence, the nip loads are not equal. Due to the increase of the roll weight the nip increases during the run from 2000 N/m to values higher than 10 000 N/m. Hence, it can be anticipated that the WOS would increase when the diameter increases.

The rolls were unwound in our pilot winder in Järvenpää using LDV 1 and LDV 2 of Figure 1. The running speed was 500 m/min. The measured strain difference of all four rolls is shown in Figure 4. Indeed, the strain difference increases with the diameter as was expected. Also the rolls run in the same sets have nearly equal strain differences. In the curves of roll 3 of set 3 and roll 4 of set 4 there are same irregularities at 900 mm and 1200 mm, respectively, which are due to measuring error of one of our LDVs. Apart from these small deviations the shape of the curve shapes look as one would expect. However, the level of the curves is something that we cannot explain. Based on the lab measurement of the tangential modulus and paper thickness the estimated strain at LDV2 is approximately 0.12 %. In Figure 4 most of each curve is below -0.12 %, which would mean that the WOS is negative. This cannot be true. We don't have any good explanations for this. Based on mechanical alignment measurements and on the general shape of the WOS curves measured from rolls run with constant nip loads we have estimated that the alignment error to be less than 0.5 degrees. According to Table 1 the resulting speed measurement errors cannot explain that big differences. The increase in the strain difference between 400 mm and 1400 mm is about 0.06%, which would result in increase of 350 N/m in the Wound-On-Tension. This is at least plausible.

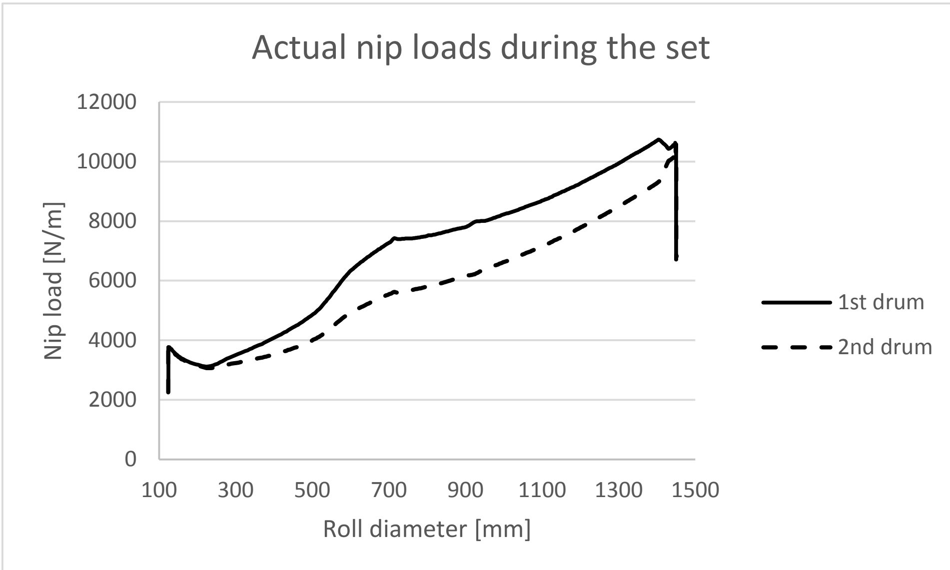

Figure 3 – The resulting nip loads in the containerboard run on a two drum winder

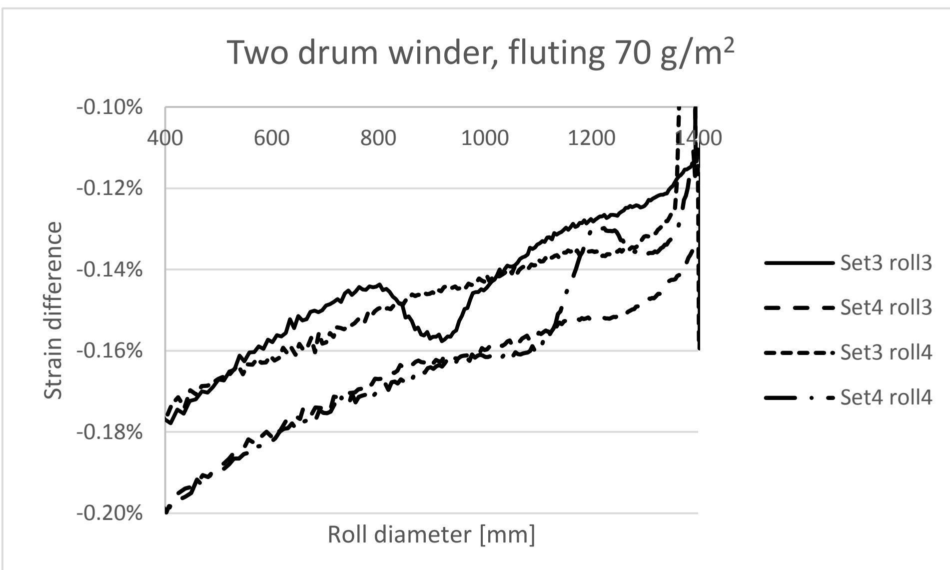

Figure 4 – Measured strain differences (unwind - web) from 4 fluting rolls

Influence of the unwind speed

Since we got surprisingly low strains with the unwind option method also the influence of the operating speed of the winder on the results was evaluated.

Two tests were made with 70 g/m^2 containerboard. In the first test the initial speed was 50 m/min and then the speed was increased in steps to 100, 200 and finally 500 m/min. In the second test same paper grade was used but now we started at speed 500 m/min and then after having unwound 2000 m of paper the speed was reduced to 50 m/min. After running another 2000 m of paper the web tension was increased from 700 N/m to 900 N/m keeping the speed at 50 m/min. Figure 5 shows the measured strain difference in the first speed test. At speeds 50, 100 and 200 m/min the speed difference remains practically equal but at speed 500 m/min, when the unwind roll is already quite small, the difference starts to increase towards the roll bottom. The shape of the strain difference at speed 500 m/min is probably due to the alignment error of the unwind LDV and is hence not reliable. In the second speed test the average strain difference at 500 m/min is about 0.075 % and at speed 50 m/min, when the tension is 700 N/m, about 0.069% and at speed 50 m/min and tension 900 N/m about 0.097 %. The conclusion is that the unwind speed has negligible influence on the measured speed difference.

On the other hand the tension increase of 200 N/m produced significant change in the strain difference: 0.028 %. This enables calculation the estimate of the web stiffness K

$$K = \frac{200}{0.028\%}\ \text{N/m} = 0.72\ \text{MN/m}$$

The web stiffness can be used to calculate estimate for the Wound-On-Tension (WOT) from the measured Wound-On-Strain (WOS). When the web tangential elastic modulus is calculated from the stiffness we get the value 7.7 GPa, which is of the same order but higher than the tangential modulus measured in laboratory where the result 6.6 GPa was obtained.

Figure 5 – Strain difference in the first speed test

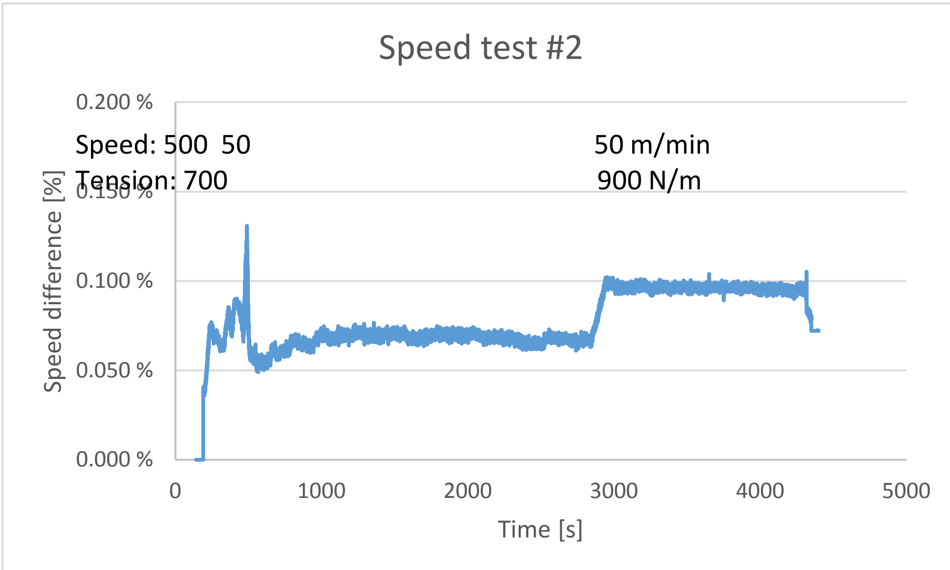

Figure 6 – Strain difference in the second speed test

<u>Unwind and wind up WOS measurement of WFC matt grade run on a single drum winder</u>

We wanted to compare the WOS measurements made in the wind up and unwind by first applying the wind up measurement on a 200 g/m^2 WFC matt grade run surface wind mode with a constant web tension and nip load on our single drum winder. In the second phase the same roll was rewound while making unwind WOS measurement. The winder was equipped with a winding drum having 12.5 mm thick, nearly incompressible, elastomer cover of hardness 78 ShA.

Figure 7 shows the WOS measurement results. The unwind strain difference increases about 0.025 % from diameter 400 mm to 1300 mm. Utilizing the laboratory measurement results of the tangential modulus 8 GPa and paper thickness 175 μm we can estimate that the corresponding increase in the WOT is about 350 N/m, which is plausible. However, with the strain level ranging between -0.075 % and -0.05% we encounter again negative values of WOS, which are not possible. Again we don’t have explanation for that.

The wind up strain difference measurement result is positive in the diameter range 400 – 1300 mm and it decreases with diameter. The decrease of the strain difference is quite big 0.13 %, which corresponds decrease of 1800 N/m in WOT. This is in principle possible but not plausible, since the web tension and nip load were kept constant during winding.

Ideally the two curves of Figure 7 should coincide. However, they seem be more like distorted mirror images of each other. For example the bump at 1000 mm is seen in both curves but in wind up measurement the strain difference increases while as in the unwind measurement the strain difference decreases. This also a phenomenon, which we can’t explain.

This web is much stiffer than the containerboard considered in the previous examples. Hence, one would expect to measure much smaller strain difference when running these two paper grades with the same winding parameter. This is the case with the unwind measurement where with containerboard the increase in strain difference was about 0.06 % whereas with WFC the increase was about 0.025 %. However, the wind up measurement's 0.13 % decrease of the strain difference is much bigger than what was observed with containerboard unwind measurement.

Based on this example it seems that the wind up measurement does not give results which are making much sense. With unwind measurement the shape of the curve as a function of the roll diameter seems plausible but the strain difference level is far to low.

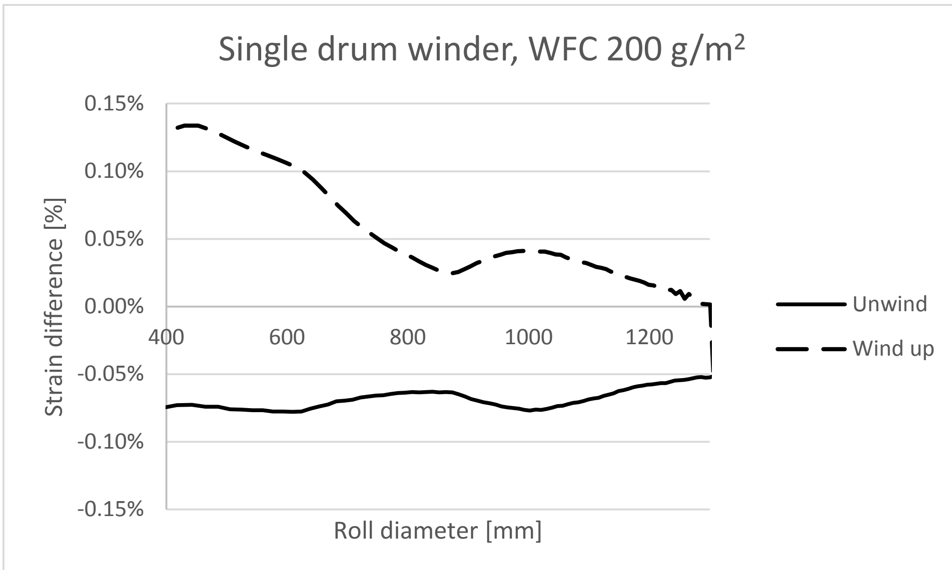

Figure 7 – Wind up and unwind WOS values for the same 200 g/m^2 WFC roll

Wind up strain difference measurement of 45 g/m^2 newsprint vs. Cameron test

We wanted to compare the wind up WOS results with the WOS obtained from Cameron test [8]. We chose a low stiffness paper grade for this study in order to facilitate both, LDV and Cameron, measurements. Again the roll was run on our single drum pilot winder with constant web tension 500 N/m and nip load 3000 N/m. The speed was 1000 m/min. The Cameron test was done about ½ - 1 ½ hour after the roll was run.

The WOS measured with LDVs at and with Cameron test are shown in Figure 8. The most striking difference is that the curves lie about 0.2 % apart in terms of strain. This corresponds to about 700 N/m difference in the WOT. It is hard to believe that that big difference could be accounted only due to the stress relaxation. The LDV WOS-curve shows decreasing trend of 0.07 % (250 N/m) in the diameter range 400 mm to 1100 mm whereas the Cameron curve is relatively flat. Like in the previous example it appears that the WOS estimate obtained with the wind up LDV measurement yields too big values. The curve shape is decreasing with diameter as in the previous example.

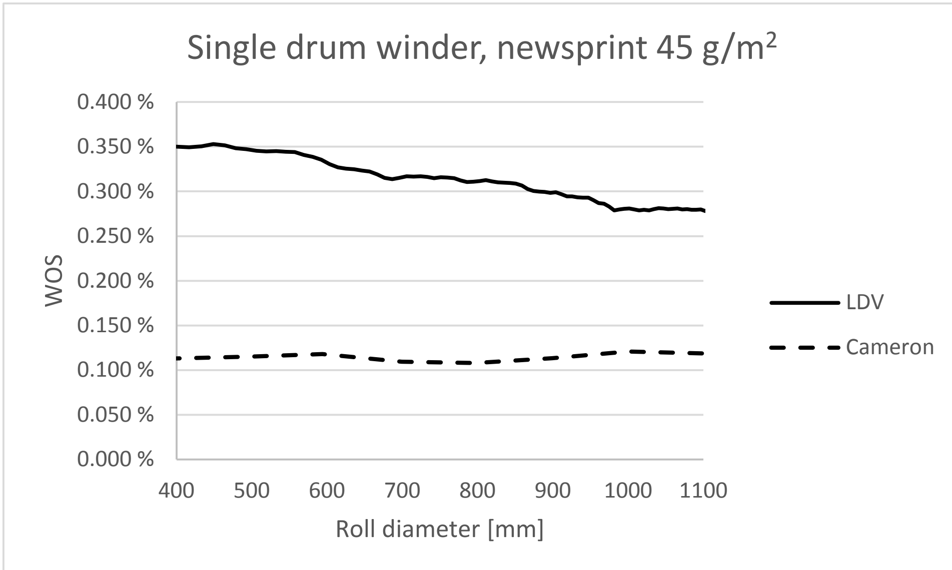

Figure 8 – The WOS measured with the LDVs and Cameron test

CONCLUSIONS

The main issue with the unwind WOS measurements was that the measured strain difference values were clearly too small. In principle very big alignment error could explain that but then one would expect the strain difference to increase a great deal when the roll in the unwind becomes smaller. We could not see a general trend of that. On the other hand the wind up strain difference measurements seemed to give too big values. That cannot be explained with alignment error.

In the future we should concentrate on finding the sources of error in the measurement set up. One thing would be the study of sensibility of the LDVs on the environmental conditions. For example we have noticed that once and a while one of the Laser BetaMike's LDV produced abrupt 0.1 % changes in the web velocity measurement in stable conditions. When a powerful light was applied to the web the velocity measurement was stabilized. We need to understand what the reason is for this.

In the other trials we were able to confirm that the web tension did not have any influence on WOS in surface wind mode. This result is complying with the results got in WHRC [5]. In another test we were able to demonstrate that the changes in the nip load made during running a roll remained clearly detectable when afterwards a WOS unwind measurement was made. This encouraged us that the applied method is able to detect changes in the roll structure even if assessing the absolute values was not possible.

REFERENCES

1. Paanasalo, J., "Modelling and Control of Printing Paper Surface Winding," Doctoral Thesis, Helsinki University of Technology, 2005.
2. Good, J. K., Kandadai, B. K., and Markum, R. A, "New Method for Measurement of Wound-in-Tension in Webs Wound into Rolls," Proceedings of the Ninth

International Conference on Web Handling, Stillwater, Oklahoma, June 10-13, 2007, Oklahoma State University, pp. 77-92.
3. Kandadai, B. K., “The Development of Wound-on-Tension in Webs Wound into Rolls,” Doctoral Thesis, Oklahoma State University, Stillwater, Oklahoma, 2006.
4. Jorkama, M., “Contact Mechanical Model for Winding Nip,” Doctoral Thesis, Helsinki University of Technology, Espoo 2001.
5. Good, J. K., Kandadai, B. K. and Markum, R. A., “New Method for Measurement of Wound-in-Tension in Webs Wound into Rolls,” Proceedings of the Ninth International Conference on Web Handling, Stillwater, Oklahoma June 10-13, 2007, Oklahoma State University, pp. 77-92.
6. Pfeiffer, J. D., “Nip Forces and Their Effect on Wound-In Tension,” Tappi Journal, Vol. 60, No. 2, 1977, pp. 115-117.
7. Pfeiffer, J. D., “Wound-Off Tension Measurement in Paper Rolls,” Tappi Journal, Vol 60., No. 3, 1977, pp. 106-108.
8. Routine Control Method RC 317, Cameron Strain Test. Tappi Journal, Vol. 46, No. 12, 1963, p. 123.