CALCULATION OF FILM TENSION FROM FILM POSITION AND ROLLER POSITION

By

Günter Oedl
Brückner Maschinebau GmbH & Co KG
GERMANY

ABSTRACT

The web tension as a crucial parameter for a web line is normally manually influenced by the speed of the motors driving the rollers. This paper shows that is better and easier to use the roller position derived from the motor position. For each roller there is a point where the web has the same speed as the roller surface. For each time step we read from the increase of the roller position during this time step (length of roller surface passed during that time step) the amount of material transported during over one roller. Looking at one web span, we know how much material has entered in that span over the roller in front of that span and how much material has left over the roller behind that span. This leads to the elongation of the material in that span. From the know Young's modulus we can calculate the web. The benefit is, that this calculation is independent of line speed and also works at stand still of the line. This type of calculations is very simple and useful for stationary effects (long-term effects) and also dynamic effects (instant changes in speed).

NOMENCLATURE

angle_1, angle_2 angular position of roller 1 (2,..) in rad. The value increased according to the rational speed of the roller. Values go from 0 (at start of calculation) and go to infinity.
elong_i : elongation of span I (between roller i-1 and roller i)
mv_rol : motion of each roller surface for any time step
r1 radius of roller1 (r2 radius of roller 2,…)
x_line : coordinate of web pass line in m
x_r1, x_r2, .. position of roller surface, that is the length of a roller 1 (2,..) surface travelled from starting of calculation (or simulation)
x_web : coordinate of web pass line in m of original web

TENSION CONTROL AS USED TODAY

For web handling, the longitudinal web tension is for sure the dominant influence for the behavior of the web. Wrong web tensions can harm the web, create troughs or wrinkles and can lead ultimately in web breaks. The tension in a free span between two rollers is hard to measure directly [1]. The control of the web tension is via the control of the electronic drive, which rotate the rollers. There is a wide literature in all of the preview IWEB conference here at OSU. A good overview of the basic can be found in [2].

The last decades brought some changes in drive technology:

- Drives have moved from DC drives to AC drives
- The speed feedback has developed from analogue tachometers (Volts/rpm) to digital position encoders giving the angle of the roller with a precision of some ten arc seconds (1/130 000 of a rotation) [3].
- The motor control has changed from hardware based analogue circuits to digital control.
- The accuracy and the speed of these new controls are enormous: control cycle periods are below 1 ms (frequency is above 1 kHz). Speed and position can be measured in the order of 0.01 % or even below.
- Those new motor controllers allow user defined calculation by the use of free function blocks.

This paper shows a way how to take advantage of these new features to calculate the web elongation and from that the web tension by using the roller position instead of roller speeds.

Manual Speed Control

This is the most common control mode. The operator sets the speed of each motor. This is typically done via an “overspeed” factor is an addition (or factor) to the previous motor speed. Each motor can drive one roller or a group of rollers. The setting of the speed setpoint is done by the operator. His input for his decision to increase the tension via speed (or the other way) is his visual inspection of the web in the line.

Manual Torque Control

If the web is fixed at a “strong” roller or a speed controlled unwinder at one position, it is possible to control the next roller with a fixed torque. This creates a well-defined force to the web. But as all roller downstream contribute also to the first web span, this only an option for a small number of lines.

Automatic Tension Control with Load Cells or Dancers

This requires a tension roller (driven or undriven roller) or and dancer roller on the web. This is a standard procedure creating a certain cost for the load cell in the bearings of the tension roller (or the dancer). The control is pretty easy under following conditions.

- The Young’s modulus and web thickness (and web width) do not vary to much
- The variation of speed of the line is not to high
- The speed ramp for the line is moderate.

There is a long list of papers here at the previous IWEB conferences on control with load cells and dancers under different conditions.

Observer Based Tension Indication and Control

There are some solutions that use the motor speed and motor as input and calculate the web tension from that. Some of them use this web tension for a closed loop control [4].

All above strategies have the ability to give good results for steady state and slow changes of tension setpoints, speed of line or slow changes external force. “Slow” in this sense means that these values only change significantly over a period, which is much longer than the travelling time of the web through the web span.

All these controls are based on pure proportional control, because the integral part is already in the system: a speed change integrates into a change of elongation and a tension. Mostly the control is decentralized, that means each span is considered to be independent from other spans and the influence of the other spans is small to the adjacent spans.

PHYSICAL BACKGROUND

The need to make any of the above controls faster leads to the idea for a derivative part in the control. A derivative part will react very fast on a change of one of any of the inputs. As widely known: The derivative part in a control increases the noise and makes the system jerky.

So we better take a closer look, what really determines the tension:

For simplicity of the model, we assume a web following the Newton’s law of elasticity and ignore visco-elasticity, higher order elasticity or thermal expansion. This can easily be included in this system later, but is not part of this paper.

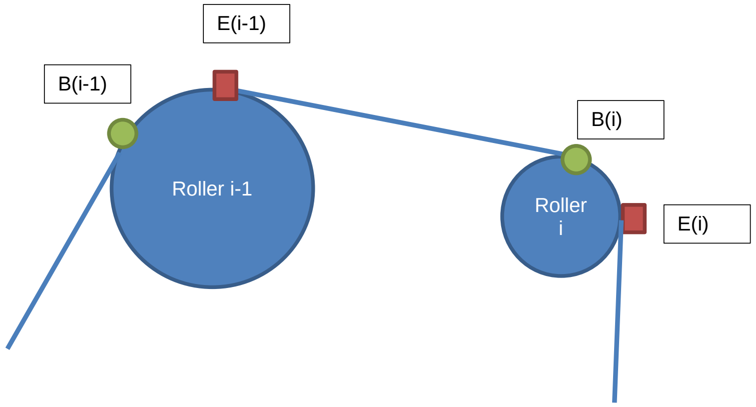

Figure 1 – General View of Web Path with Beginning of Contact Zone “B_i” and Ending of Contact Zone “E_i”

Each roller i has a point, where the web touches the roller i. We call it the “Beginning Point of Contact ” B_i. The point at the end of the contact with the roller we call the “Ending Point of Contact” E_i. The length of the web span is the distance of E_i-1 to B_i. From a known geometry of a line (given position of center of rollers and given roller radii), we can calculate the length of the web span. We also can calculate the length of the web on each roller: arc from B_i to E_i. The speed of the web in the span is the same as the following roller [5]. Therefor a speed change (and a change in elongation or force can only occur at the points E_i.

Rem.: At a closer look the speed change does not occur directly at the position E_i, but in a slip area just in front of this [5]. This creates only a minor error here, but will be considered in a future update of this work.

We also assume that the web had some marker on its surface showing every meter (or mm) of the web at the initial state of the web, like a printed cloth with a defined pattern of lines. If the web is stretched, those markers separate, but always refer to their original distance. In reality this makers could really put on the web to illustrate the behavior. This would be very hard to measure in a running line and not needed for the calculation.

We define two sets of length coordinates, both measuring the way the web travels:

x_line is the length at the pass line of the web. It can be imagined as a stiff measuring tape, which had been inserted in the line before startup. The position of the relevant points B_i and E_i of each roller is constant in x_line for the lifetime of the machine.

The other length coordinate is x_web, this is the length of the web, running down the same path, but the units are the meters of original web (at the beginning of the line). During the operation of the line for any of the relevant points B_i and E_i the value of x_web is constantly increasing. After a certain time at E_1 the value will be 10 m. This means that at this instant 10 m of web have passed through this point. At the same instant at the position E_2 the value in x_web might be 9.2 m. A second difference to the reference coordinates x_line is that the length x_web is not the physical distance from E_2 to E_1 in the above example, but it refers to the original length of web at the beginning of the line. So at any point the comparison of the positions in x_web with the ones in x_line give us the elongation state of the web.

As stated above the web speed only changes at the points E_i, we concentrate at the values of these points in the coordinates x_line and x_web. We track over the time the web length x_web at the relevant points E_i.

LINE LAYOUT OF SAMPLE LINE

Here we show a small line with 6 rollers and the web running from left to right. The important points E_i are shown as square markers:

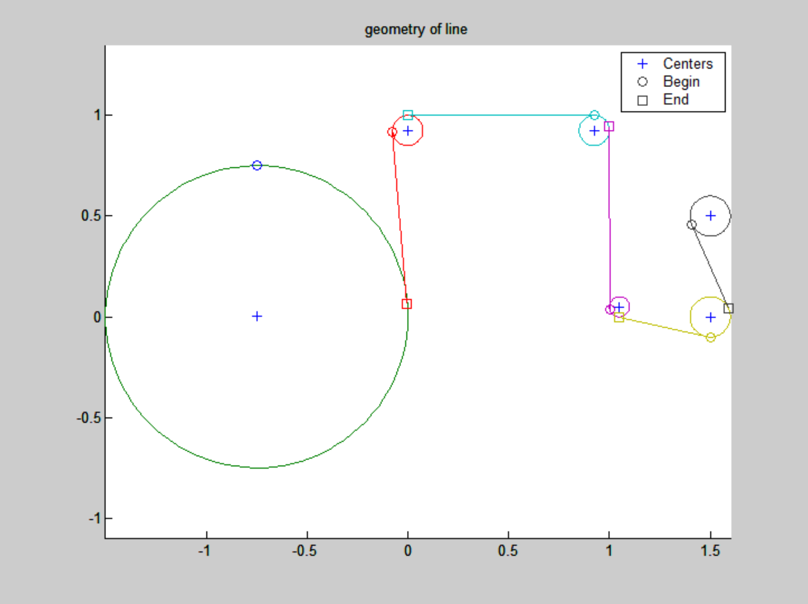

Figure 2 – Sample Web Line

We start our calculation at the instant, when the x_web = 0 has reached the point E_6. That means the line has been threaded up or the first part of web has reached the end of the line.

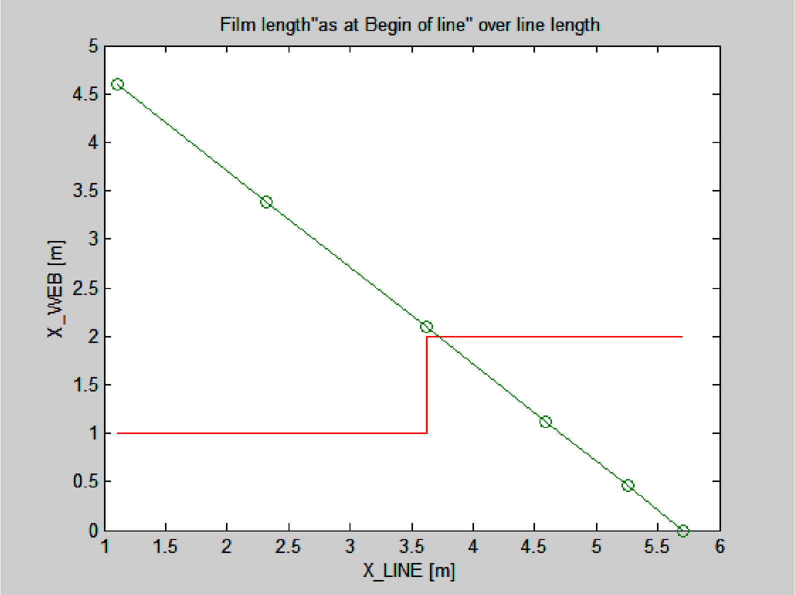

Figure 3 – x_line at the Starting Point (Falling Line with “o” Marker) and Roller Speed (Line with Step -) Speed Increase between Roller 2 and Roller 3

The green (falling) line shows the x_web over x_line. In the first step, this is a -45 degree line: no stretching of web at all. To make the starting point easy to understand, we have deliberately chosen the point, when the web length (x_web = 0) has reached the end of our line (x_line = 5.6m).

Rem.: Please note, that the direction of x_line goes left to right (downstream rollers will have a higher value) whereas the x_web goes right to left and showing web parts with a higher number being closer to the start of line. As a result, the line goes down.

CALCULATION OF WEB MOVEMENT AND ELONGATION

For this starting time of the model at the beginning of the line, x_web = 4.6 and the we start we no elongation in the web. This will change later. During running the line, we take for every time step the move of each roller.

Rem.: The time step should be so small, that the move is small compared to the web span length.

For every roller we calculate the move “mv_rol_i” for one time step, i.e. speed of roller times the time step for the simulation or the actual change in surface position according to the encoder.

Now we look for the web length (x_web), which will be at the points E at the end of this step. Is must be the point, which is exactly mv_rol_i upstream of the point E before that move. This can be done with a linear calculation.

The good thing in this type of calculation is that we only have to watch the points of web, which are at the positions E_i. We see the web as free in most of the length and only pinched to the positions E_i. After the time step, the position x_web at E_i has just move by mv_roll_i. So we need not to know about elongation or forces of web at this point of calculation.

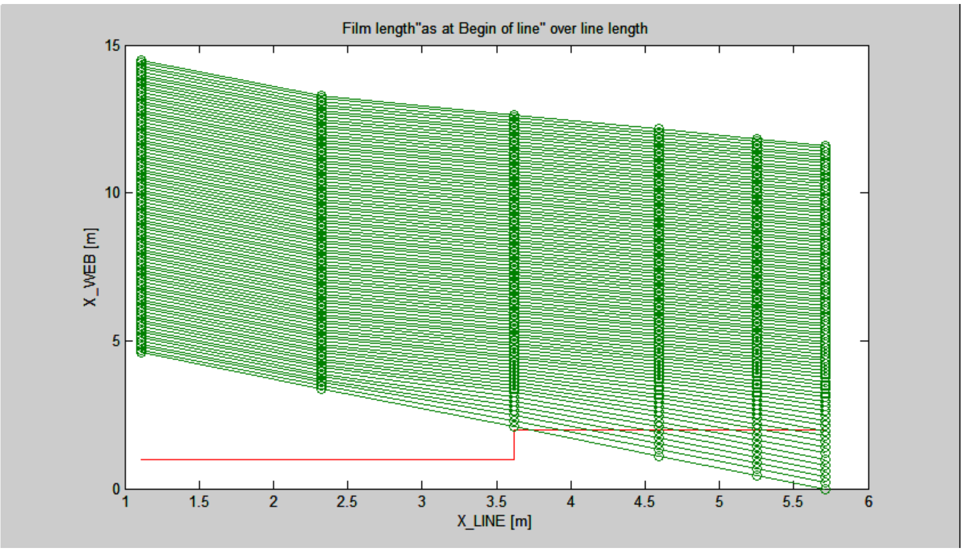

Figure 4 – x_line during 10 Seconds of Run (Falling Line with “o” Marker) and Roller Speed (Line with Step -)

As we deliberately have chosen for the start of calculation the state of web having no elongation, the first line (lowest line) is a straight line. During the calculation time, the lines move upward. It also changes towards the situation, where the web speed is lower until point E_2 (at 2.4 m). This can be seen by the steeper falling rate of the line. After 2.4 m (after the point E_2), the line is not so steep any more. This means that the web is stretched (elongated) by the roller 3 and the following rollers.

Rem.: In our example here, the speed is 1 m/s for the rollers 1 and 2. The rollers 3, 4 5 and 6 have the speed of 2m/s. This is unrealistic high speed increase, which will break the web. This has been chosen, only to have a nice visual representation here.

After having calculated the web movement we inherently know the stretching state of the web in each span as they change over the time.

At the end of each time step the stretching state is calculated as

$$elong_i = (x_{line\_i} - x_{line_i-1})/(x_{web_i} - x_{web\_i-1} \qquad \{1\}$$

We always refer the elongation at a certain span to the elongation at the beginning of the machine. The easiest assumption is that at the beginning of the machine, the elongation is zero. But if the elongation at the start of the line is other than zero and known, it can be easily incorporated.

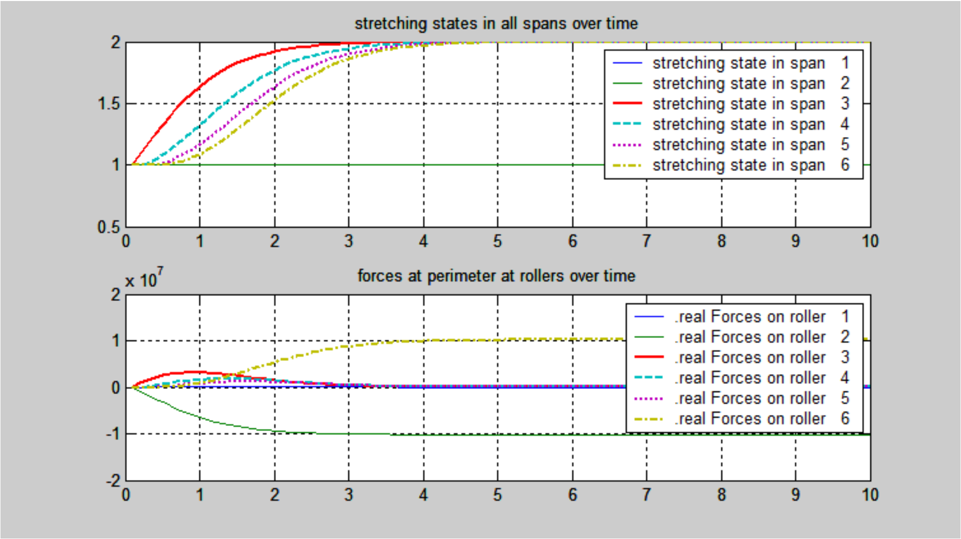

Figure 5 – Stretching State over Time (Top) and Force at Perimeter at Each Roller (Bottom)

In Figure 5, we see the change in stretching state for each span: in Span 1 and 2, the state stays 1.0. The span 3 is the first to increase (solid line). All other spans only see the increase of stretching state later. It can be understood, because in the first moment the span 4 runs with the higher speed, but has still the stretching state of 1.0. Only when the material, which is stretched (or elongated) at the point of speed jump (here roller 3) reached downstream the span 4, the stretching state increase.

From the known stretching state we can easily calculate the force in each span by using Newton's law of elasticity.

$$force_i = \text{elong\_i* K\_i} \qquad \{2\}$$

where K_i is a constant factor (spring constant of web)

$$force_{\_perimeter\_i} = \text{force\_i-1 –force\_i} \qquad \{3\}$$

The force onto each roller is the difference of the web forces of the adjacent spans. The force on the perimeter can be easily be transferred to roller torque and motor torque.

In Figure 5, we see that during the transition phase some unexpected variation of forces onto the rollers. This shows the clear-out-phase of the web material at a speed, which does not represent the elongation state. This is the realistic case, because during this transition phase the web runs fast, but still has the low (at beginning zero) elongation. With other words: this model explains the transport of web with the relevant stretching state, which is present at every web line. But may simplified tension models do ignore this and therefore predict wrong tensions during speed change. So this model represents the real state of elongation and forces in the web for steady state and dynamic changes.

PRECISION OF CALULATION

Besides the simplicity of this calculation, this model allows a very precise calculation of the elongation and forces: for a typical roller configuration, the radius is 100 mm (diameter 200 m). If the encoder allow as resolution of 10 arc sec, the resolution of position at the roller surface res_x is

$$res_x = 0.2\ (m) * pi \frac{10}{360*60*60} = 5\ \mu m \qquad \{4\}$$

The smaller the roller or higher the resolution of the encoder are, the better the resolution gets. We have to compare this resolution of the position to the length of web span. For a typical line, we assume this as 1 m. So we get e resolution of $5*10^{-6}/1$ = 1/500000, which is quite impressive.

In this model we assume, that each roller has motor and an encoder, both directly linked to the roller: we call this a direct drive system. If this is not the case, because a gearbox and a belt are used, the roller position can be easily be calculated by the known gear ratio out of the motor encoder. But for a precise control, a direct drive is anyway preferred [4].

This model does work for driven rollers, but also in the same way for idler rollers, if they have an encoder mounted. If idler rollers are used without an encoder, the complete span for driven roller to driven roller -including the wrap on the idler roller(s) - is considered as one span.

CONCLUSION

The described way of calculation, the web being transported has the following benefits:

- Easy to implement
- Easy to understand, because it does not need partial differential equations
- It uses the roller (or motor) position, which is free accessible at modern drive system
- It is very robust to small speed variation, coming from any source (process, roller bearings, unbalanced rollers motors or couplings, etc.)
- It works at any speed including stand still.

- It can easily be improved for any complex type of elasticity by changing the formula {2} accordingly.
- It does not rely on the torque output of the motor control, which is very often not accurate.

REFERENCES

1. Vickery, Curtis M., and Lowery, Richarld L., "Measurement of Web Tension Distribution by Point Source Pulse Excitation," Proceedings of 2nd Intl Conf. on Web Handling, Oklahoma State University, June 6-9 1993.
2. Rosium, D., The Mechanics of Rollers, Tappi Press 1996 ISBN: 0-89852-313-3.
3. Heidenhain., N. N., Product Info Rotary Encoders with Plane-Surface Coupling, http://www.heidenhain.com/fileadmin/pdb/media/img/1085677_02__D_02_ExN_13xx_Aufzugtechnik_en.pdf
4. Oedl, G., "Tension Control in Thin Film Productions Lines." Proceedings 8th Intl Conf. on Web Handling Proc., Web Handling Research Center, Oklahoma State Univ, June 5-8, 2005.
5. Brandenburg, G., "New Mathematical Models and Control Strategies for Rotary Printing Presses and Related Web Handling Systems," Proceedings of 18th IFAC World Congress, Milano (Italy), August 28 - September 2, 2011.