TENSION CONTROL IN THIN FILM PRODUCTION LINES

by

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ABSTRACT

A comparison of speed and tension control in pull roll stand at film production lines is given. One typical error (periodic error) of standard gear box drives is analyzed and discussed. The design of a active tension control based on observer is explained. The simulation environment is shown. Results from production lines at various film thickness (4 to 25 μm) are shown.

NOMENCLATURE

E	kinetic energy in the system
i	total transmission ratio from motor to roll (gear boxes and belts)
J_2	momentum of inertia
MD	machine direction
r	radius of pulley (or cog wheel)
TD	transversal direction
ω	rotational speed [rad/s]

INTRODUCTION

The tension control is an essential task in web handling. Besides the obviously understandable limits of exceeding the breaking force or reducing the tension below 0, the actual tension will strongly impact the web behaviour for creating wrinkles or web defects. This subject has been focused by many works in IWEB conferences [1] [2]. The actual web tension can be directly measured by tension rolls. These rolls increase the complexity of a web handling machine and create extra costs. Therefore the use of tension rolls is limited to a few implementations.

The majority of web handling machines are based on a speed setting, where a speed cascade defines the surface speed of adjacent rolls. Still widely in use are mechanical speed cascades, where the speed is defined by belt drives or gear boxes, which drive several rolls by one motor. The advantage of little costs is often contradicted by the inflexibility to changing process requirements and pose extra error. Most today's system use individual motors for each roll and each motor is electronically controlled. This leaves the problem of speed setting to the operators, who often find it hard to control a high number of speed setpoints. This paper gives an update on web tension control on film producing lines.

CURRENT SITUATION

Biaxial film lines for PP, PET, PA and similar products consist of an extrusion part, casting wheel, where the primary or cast film is created. This film then is stretched in both directions (MD and TD) either with two subsequent machine parts MD-orienter and TD-orienter or in a single step, a simultaneous stretcher [3] [4].
After the stretching the film runs through the pull roll stand, where the edge of film is trimmed, the thickness and other properties are measured and a surface treatment (corona or flame treatment) is done. Finally the film is wound to rolls on a center winder. Current film width can be up to 10 m and film speeds go up to 550 m/min.
Rolls are currently driven by AC motors, this can be induction motors or permanent magnet motors with a speed feedback system. DC motors are used in a strongly decreasing number, mainly because of their high maintenance costs and lower efficiency. The standard speed feedback uses an encoder with rectangular or sine wave form, latter giving a higher resolution in position and therefore also in speed.
When a web is transported over rolls, most rolls are driven by motors. We have to distinguish between following drive concepts:

1. Idler rolls: roll is driven by film.
2. Group drives: 2 or more rolls are driven by one motor. The individual rolls might have identical surface speed or a mechanical speed ratio, which itself can be constant or changeable by tapered pulleys. For this group of rolls one speed setpoint can be given and one value of actual speed and actual torque is available from the drive.
3. Individual drives: each roll has a motor which is controlled electronically. The roll is driven via a gearbox and/or belt.
4. Direct drives: This is a subset of the "individual drive" concept, where the motor is linked directly to the roll, i.e. the motor has the same speed as the roll.

The idler rolls are not addressed in this paper, because they are rarely used in film production lines. One reason for this is, that for emergency stop also these idler rolls have to be decelerated quickly.
The last category is the most expensive one, but gives some advantages to the upper ones: Comparing with the second type the individuals drive concept gives a maximum freedom in setting the speeds, i.e. influencing the tension in the web. Compared to the third choice the roll is linked stiffly to the roll, so the speed of the roll is indentical to the speed of the motor.

The current situation is a combination of group drives and individual drives with a mechanical gear and belt system. The standard control is an individual speed control at each drive with a speed cascade, i.e. the actual speed setpoint of a roll is the speed setpoint of the previous roll multiplied by a factor (normally in the range of 0.90 to 1,10). The linkage by the web between adjacent rolls is typically neglected at the design of controller. But typical a slow controller setting ensures a stable control and filtering of the speed signals is used to eliminate all fast periodic errors. The operators estimate the film tension, mainly by observing wrinkles and the sag of the web. As lines are getting faster and the number of drives increase, the task of setting the line speed right is getting more and more challenging. Each mistake in setting the speed ratios can lead to a web break. Furthermore the quality of speed setting can only be characterized by the visual impression and contradicts the today's quality standards, where a measurements and trending is required.

NEW DESIGN OF TENSION CONTROL IN THIN FILM LINES

Periodic Errors in Speed and Torque

At different lines with individual drives with gear boxes a precise measurement of motor speed and roll surface speed showed following behaviour:

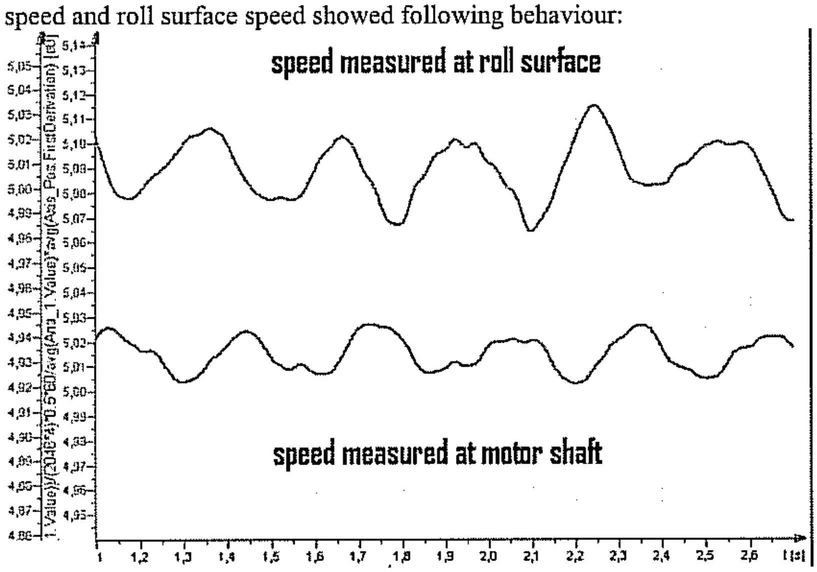

Figure 1: speed at roll surface (top curve, left scale) and at motor shaft (bottom curve, right scale) of individual drive with gear box.

The top curve shows the speed measured at the roller surface with a measuring wheel and a speed encoder (SinCos speed encoder 5000 periods/revolution). The lower curve shows the speed measured at the motor shaft with the standard speed encoder (1024 square signals /revolution). Both signals show the same dominant frequency (3,3 Hz), but with a phase shift close to 180 degree. The amplitudes are relative small (0.17 % at the roll surface and 0.095% in the motor speed), but the effect is rather important as we will see in the next chapter. Whenever the speed of the roll surface rises, the speed of the motor decreases. This effect is caused be non linearity of the gear box or the belt pulleys. In this case it was traced to the first cog wheel of the two stage gear box. We call these errors a periodic transmission error. An easy understandable example is a pulley with an eccentric axis.

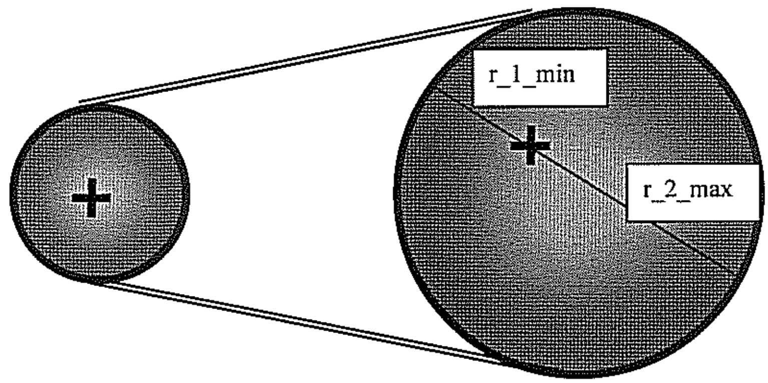

Figure 2: periodic transmission error example: pulley with an eccentric axis.

Imagining a perfectly constant motor speed ω_1 (left pulley) the roll would be accelerating and decelerating according to:

$$\omega_2 = \omega_1 \frac{r_1}{(r_2\_\max + r_2\_\min)/2} * (1 + \Delta\omega_2 * \sin(\omega_2)) \qquad (1)$$

Where $\Delta\omega_2 = 2 * (r_2\_\max - r_2\_\min)/((r_2\_\max + r_2\_\min)$ (2)

The angular velocity will go up and down in this example with the varying radius. As the moment of inertia J_2 of the roll is considerable, the acceleration and deceleration of the roll requires significant power. As long as the bandwith of the speed controller is low relative to ω_2, the controller cannot react on this error and our assumption of ω_1 being constant will not be true.

As the controller (and the motor) will not provide a dynamic torque, the speeds ω_1 and ω_2 will follow the law of energy conservation:

The total energy is $E = \omega_1^2 * J_1 + \omega_2^2 * J_2$ (3)

To keep to that law, whenever ω_2 goes up ω_1 must go down. For a better understanding of the relation, J_1 is often transferred by

$$J_1' = J_1 * i^2 \qquad (4)$$

to the speed of the roll. Now J_1' can be compared directly to J_2:

J_1' >> J_2 : the effective inertia of the motor is much bigger than the inertia of the roll, so the speed variation occurs mainly on the roll.

J_1' = J_2 : the effective inertia of the motor equals the inertia of the roll, so the speed variation occurs at same magnitude on both sides.

J_1' << J_2 : the effective inertia of the motor is much smaller than the inertia of the roll, so the speed variation occurs mainly on the motor.

An analysis of the most widely used drives at BO-film lines showed the ratio J_1' /J_2 being mainly between 0.05 to 0.3 with some values going up to 1.3 !!. The latter being a motor with 3000 rpm driving a roll with 26 rpm (i=82).

As the bandwidth of speed controllers going up to ensure a fast an precise control, the speed control tries to counteract the variation of ω_l . This results in high torque variation :

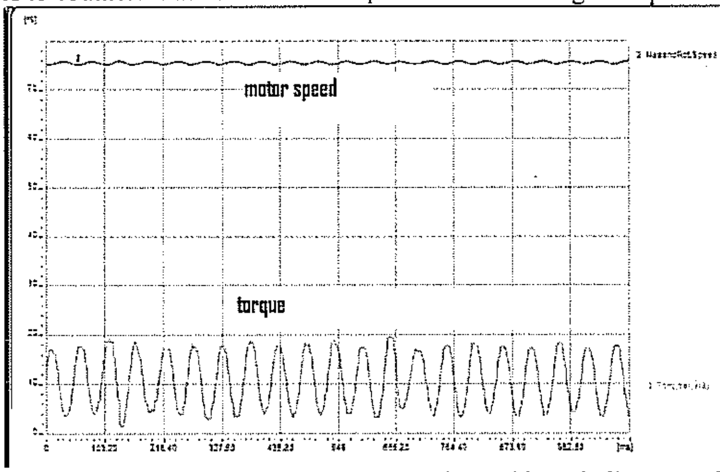

Figure 3: Motor speed and torque at a gear box with periodic error of 0,65 %.

The speed error is only 0,65 %, but the torque changes by 17 % of nominal torque. If the torque signal is used for any analysis like tension control, this torque signal is unusable in this form.

A detailed analysis shows that more than one frequency can be found, normally with one dominant frequency. The relative speed error are in the range of 0.05 % to 1 %.
Direct drives, where motor and roll have a common shaft, do not show such an error.

Direct Torque Concept

For the new film production lines each roll has a torque motor, which is directly coupled to the roll.

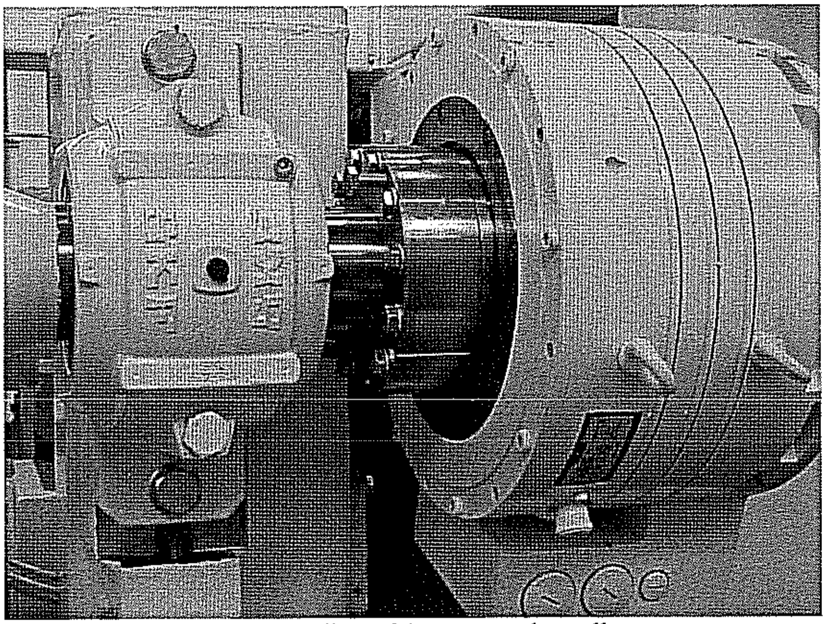

Figure 4: direct drive mounted at roll.

The rotor of the permanent magnet torque motor is mounted directly onto the shaft of the roll and is supported by the roll. The stator is linked to the frame only by a torque suspension. This allows the motor to follow inevitable small runout errors in the roll without destroying the motor bearing.

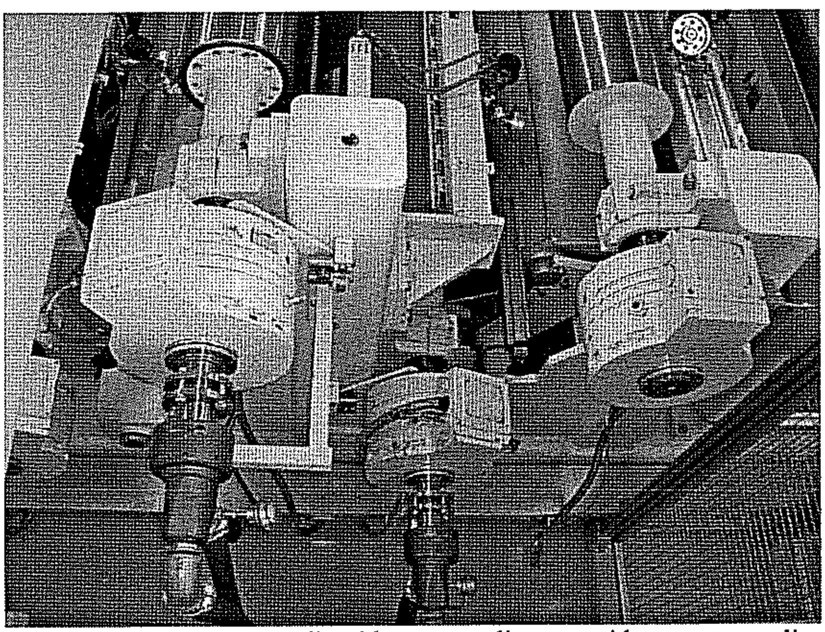

Figure 5: Pull roll assembly: two rolls with water cooling one without water cooling (right)

The direct drive concept has following advantages for the tension control:

- low friction
- very low periodic errors
- high stiffness

Friction itself would not be a problem, because it is compensated in the drive. During start up of the line the friction vs. speed is stored and compensated during production. A problem arises, when that friction changes over time, temperature or other values. A standard gear box and belt system is rather complicated to model, because of many nonlinear loops, like friction vs. oil temperature. A direct drive system has only the bearing friction, which is well analysed by the bearing manufacturer and shows very constant behaviour over life time of the machine. The only significant remaining effect for the friction is the speed.

Through the simple mechanics only the alignment of the encoder and the encoder itself are relevant for that kind of error. This error typical is smaller than 0.01 %.

The high stiffness leads to a high resonant frequency, which is required to be above band width of the speed or tension controller. In our case the resonant frequency has always been above 400 Hz.

Nominal motor torque is in the range of 200 Nm to 2000 Nm.

Active Tension Control

A control of the web tension has been implemented to directly monitor and control the web tension. The system is based on [2] and decentralized control of [5]. As this principle is well documented in the mentioned literature, here only a short description is given:

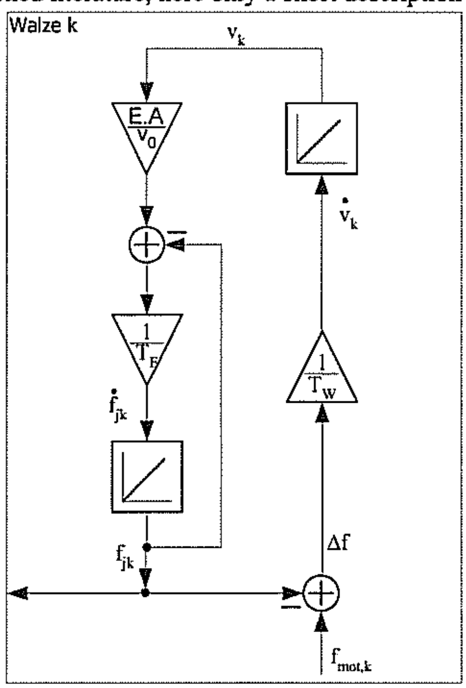

Figure 6: Signal path of a single roll without control:

All signals are displayed in linear values at the roll surface: The motor torque is transferred into linear force and the speed is given in m/s and not rpm. This is a convenient simplification against the mentioned literature. Starting at bottom right corner the motor force (torque) is reduced by the actual film force. The value Δf is the force which accelerates the roll with the time factor T_W and the integrator. The result is the actual speed v_k, which produces an elongation of the web, which results in a film force f_k. This force in its turn influences Δf and will come to an equilibrium.

This physics inherent in the roll and the web span to the adjacent rolls can be controlled in different ways:

- Constant motor torque:
  The force (=torque) of the motors is defined by the operator (or other sources) and do not change with different production situations. This is rarely used for small rolls, tendency rolls. The film speed is found in such a way that the motor force equals the film force.
- Constant speed:
  The speed of individual roll is controlled with individual speed controllers, to maintain a constant speed. The film tension and motor force will result according to the film properties.
- Tension control:
  As shown in the mentioned literature a tension observer calculates the actual film tension and sets the motor force via a state controller to maintain a constant film tension.

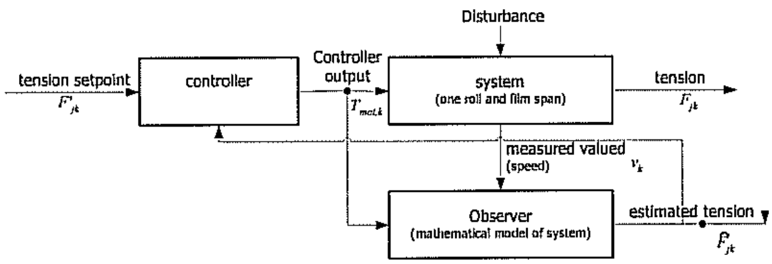

Figure 7: Observer and Controller overview:

The Observer has two inputs, the motor force (or torque) that goes to the roll and the actual speed of the roll. By knowing the system parameters, like inertia of the roll, the geometry, the film parameters etc., the observer calculates an estimated roll speed. This estimation is compared with the measured roll speed. The difference is used to calculate the film tension. This is a standard Luenburger observer [6].

The estimated tension and the actual speed are used in a state controller to calculate the motor force (torque). The design of the observer parameters is done in Matlab/Simulink :

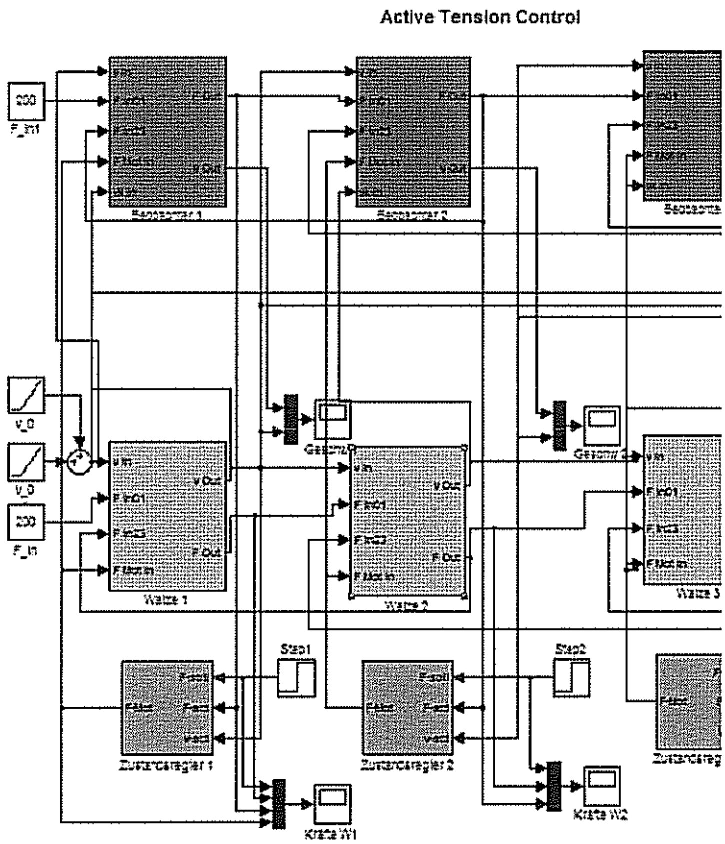

Figure 8: Simulink Model of first rolls:
The center blocks are the model of the physical system, i.e. rolls with web. The blocks in the top part are the observers and the blocks at bottom are the individual state controllers. This model allows to simulate all relevant situation of the line.

The design of the controller parameters is also done in Matlab, using pole zero map [7].

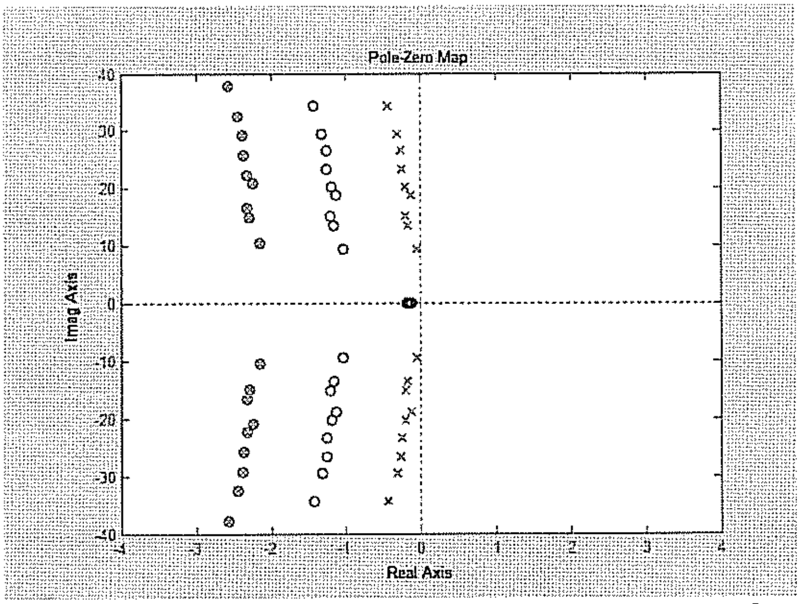

Figure 9: Pole Zero map : × poles of roll with film ; ⊗ poles of observer, O poles of controlled system.

The poles × show the dynamics of the roll and web. This is a stable system (all poles are left of the origin) but with low dampening. The poles of the observer ⊗ must be left of the poles of the controlled system O which can be set according to the needs. A fast controller means quick reaction but will also amplify the measurement noise.

The complete system then is simulated in Simulink. This allows an easy way to test the system for stability with parameter variation, such as different Young's modulus or line speeds.

Implementation

The observer and controller are implemented in the standard AC drives by using free programmable function blocks. Special effort has been taken to have minimum numeric errors due to fixed point representation. The individual drives communicate among each other via a fast fibre optic bus with an update rate of 1.6 ms.

The model assumes sufficient friction between the roll and the web. If the web starts slipping, the difference between the web speed and roll speed raises. This is monitored and the control is changed from tension control to speed control. Furthermore an alarm is issued to inform the operator.

Influences on the motor speed other than acceleration or film forces have to be avoided, namely periodic errors such as mentioned above. These would severely change the observed tension. For this reason the tension control is only suitable for direct drives.

The operator can select or deselect the tension control. Also if deselected the actual tension is displayed.

Results

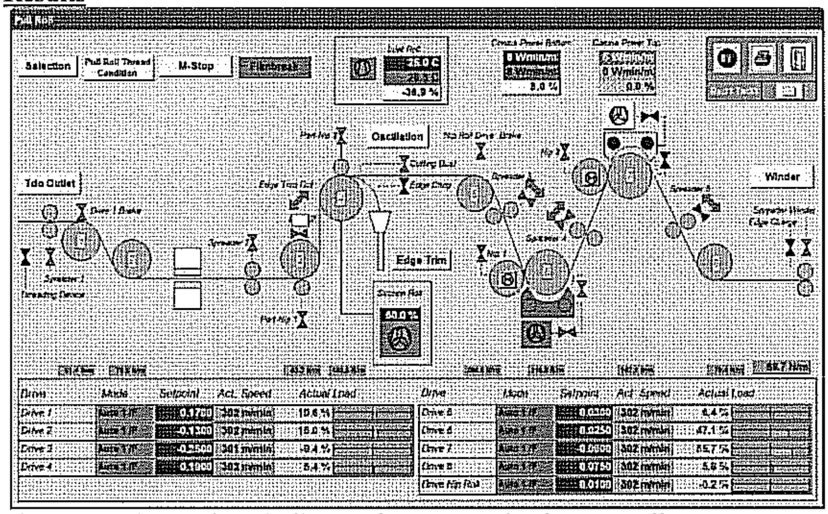

Figure 10: Film Path and Film tension at a production 7.4 m line PET at 300 m/min 25 µm.

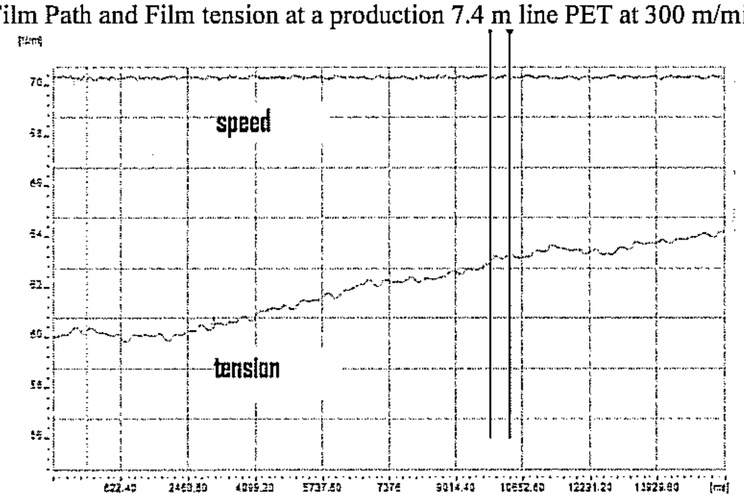

Figure 11: Change of tension setpoint from 60 N/m to 64 N/m at 300 m/min 25 µm .

In Fig. 11 it can be seen, that the change of setpoint is followed. An internal ramp transforms a setpoint step into a slope. During this change a small increase in speed must occur. But this change is so small, that is cannot be seen in the speed curve.

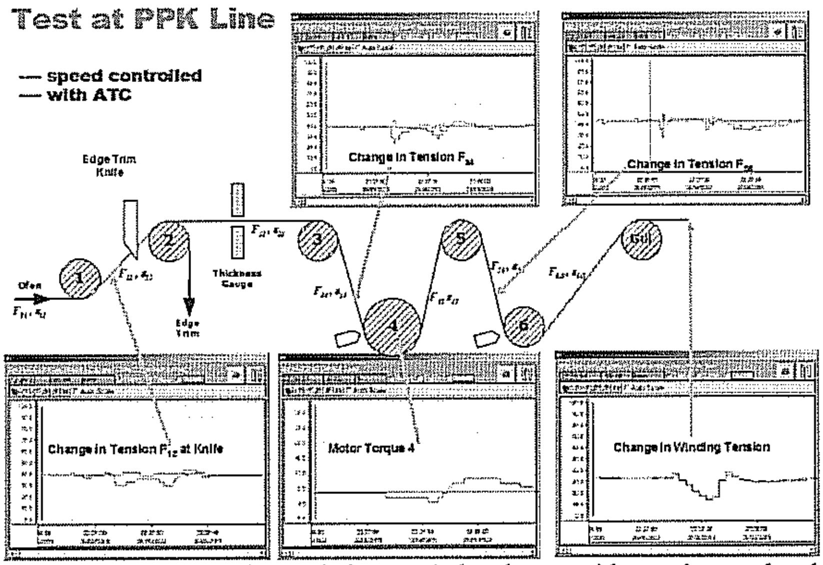

Figure 12: propagation of tension variation at winder change with speed control and tension control.

At a 4.2 m wide PP line for capacitor film with direct drives running with 4 μm thickness two tests have been made: The influence of the tension variation during winder change propagates through the complete pull roll stand from the winder upstream to the inlet, if run in speed control. Between roll 1 and 2 the edge trim knife can react very sensitive on tension variation.

With tension control the influence of the winder is compensated already at roll 6. The first part of the pull roll stand stays constant.

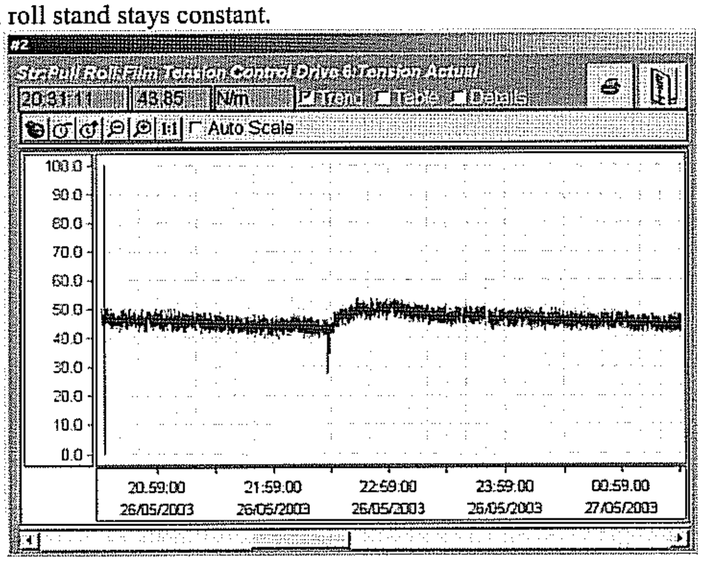

Figure 13: long term test at 7 μm film thickness (4.2 m line) speed control

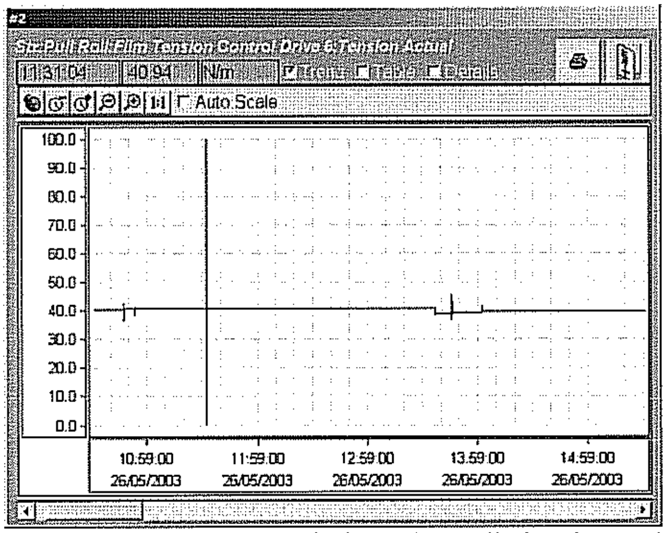

Figure 14: long term test at 7 μm film thickness (4.2 m line) active tension control

Fig. 13 shows the tension with speed control and Fig 14 with tension control. The peaks at the center in Fig. 13 and the small peaks in Fig. 14 are winder changes (ref. to Fig.12).

CONCLUSION

An active tension control can significantly decrease the tension variation in film lines. This ensures a stable production also at changing film properties and line speeds. A good drive system like direct drives is the basis for a precise observer and tension control.
A fast increasing number of film lines benefits from this system.

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Tension Control in Thin Film Production Lines **G. Oedl**, Bruckner Maschinenbau Siegsdorf, GERMANY

Name & Affiliation	Question
Duane Smith Black Clawson	Referring to Figures 13 and 14: Are those outputs speed or tension? I am assuming that they are outputs of tension and how are you measuring that on your line?
Name & Affiliation	**Answer**
G. Oedl Bruckner Maschinenbau Siegsdorf	They are both tension traces. In Figure 13 speed control was used and in Figure 14 active tension control was used. These graphs display the estimated tension. We had no means of measuring tension in this production line.
Name & Affiliation	**Question**
Duane Smith Black Clawson	Thus this is an open-loop control system and you are displaying predicted tension rather than actually measured tension?
Name & Affiliation	**Answer**
G. Oedl Bruckner Maschinenbau Siegsdorf	Yes.
Name & Affiliation	**Question**
Tong Hsu Kimberly Clark	What is the cost difference of a line with direct drive compared to a line where gear boxes are used?
Name & Affiliation	**Answer**
G. Oedl Bruckner Maschinenbau Siegsdorf	I am sorry I cannot give you an exact number. The effect is very small though because we are discussing a line that cost one million dollars. It is less than 1% than the cost of this type of machine.
Name & Affiliation	**Question**
Marcel Hage Maxcess International	If cost is not the driving factor, why would you implement this kind of model versus traditional tension control and other control mechanisms?
Name & Affiliation	**Answer**
G. Oedl Bruckner Maschinenbau Siegsdorf	The traditional approach with the tension measurement roll is more expensive. Normally, if you have a load cell, you have an extra roll somewhere to do the load measurement. If you use one of the existing rolls for the information of the load, then there is only the extra cost of the load cells, which is not high. But the load cells have some measurement error, especially if they are not calibrated and if the roll is bouncing. We believe the number of sensors in the line, at least the number of sensors which are essential for the control, should be as small as possible. The approach is that we use the torque and speed information of the drive which are very accurate nowadays, rather than using a tension roll. A benefit of this method is that we can give an estimated output of the

tension in each span, where normally rollers with tension measurement are located only in a few places in a machine. If you make a tension measurement, then you can incorporate the measurement into the control or combine and estimate the tension with the measured tension.