DISTURBANCES DURING REEL CHANGE IN PAPER MACHINES

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ABSTRACT

Paper machines operate continuously. When a machine reel is full, the paper web is transferred to an empty spool. The disturbances in the web which occur during the reel change period are wound-in and later released when the machine reel is unwound, causing disturbances in the winder and in the quality of the shipping rolls.

A measurement system was built to capture and to characterize the disturbances in web tensions and rotation speeds during the reel change period. To measure the rotation speed of the machine reel during the whole change sequence at different positions along the periphery of the pope drum a transducer with infrared transmitting of data from the machine reel to the measurement system was developed.

Large disturbances occurred due to acceleration and deceleration of the angular winding velocity of the machine reel when it moved along the periphery of the pope cylinder from the starting position to the normal winding position. The interaction between the pope and the calender section introduced rapid disturbances of the web tension. The deviation between results of measurement and simulation of an ideal winding was used to characterize the disturbances. The method can be used to study results of different ways to improve the winding. This has been demonstrated.

NOMENCLATURE

b	web width	m
d	diameter	m
F	tangential force	N/m
G	grammage	kg/m^2
h	web thickness	m
I	motor input current	A
J	mass moment of inertia	kgm^2
M	mass	kg
$n = \omega/2\pi$	rotation speed	revolution/s
r	radius of machine reel	m
S_i	web tension of section i	N/m
t	time	s
T	torque	Nm
$v_i = (V_i - V_{ref})/V_{ref}$	relative velocity difference	
V_i	surface velocity of section i	m/s
w	rotation speed of reel	revolution/s
φ	angle position of reel	radians or degree
ω	angular winding velocity	radians/s
$\tilde{\omega} = (\omega_i - \omega_{ref})/\omega_{ref}$	relative angular velocity difference	

Subscripts:

a	average
c	calender section
d	dryer section
m	machine reel
p	pope section
ref	reference
s	spool
w	web
r	reel
sim	simulation

Superscript:

c	change from steady-state operating value

INTRODUCTION

The change of a reel on the paper machine is depending on many operations which can cause disturbances. Figure 1 shows the different sections at the end of a paper machine. Paper machines usually have a very accurate draw control system which also acts as a control of the web tension. Figure 2 shows a part of the control system. Web tension measurement is included where the level of the web tension is critical e.g. in the calender section. Usually the pope drum has a torque control.

The main parameters to control the stresses in the machine reel are the web tension and the nip pressure between the pope drum and the machine reel.

The pope reeler is usually equipped with several hydraulic or pneumatic cylinders. Figure 3 shows the essential parts. The unloading cylinders are needed to reduce the nip loads because of the weight of the spool. To transfer the reel down to the rails the primary arms are moved by cylinders or electrical motors.

The Reel Change Procedure

Figure 4 shows the different steps when a machine reel is changed. When the procedure starts the spool is held by the primary arms and revved up to the machine speed by a separate drive, (a). The drive is disconnected and the primary arms move the spool towards the surface of the pope drum, (b). The first disturbance occurs when the spool makes contact with the pope drum, (c). This disturbance has an effect on the speed of the pope drum, the web tension and also the reel on the rails which is winding the paper. Then the spool is held in a stand-by position at a constant angle driven by the pope drum and waiting for the web to be shifted, (d). The second disturbance occurs when the web is shifted from the full machine reel to the spool, (e). The disturbance associated with the shift influences the reel, the pope drum and the sections before. The winding proceeds with the reel at a constant angle, (f). In the meantime the full reel is moved away to give space on the rails provided for the new reel. The third disturbance occurs when the transfer starts and spool has to move along the periphery of the pope drum, (g). The disturbance has an effect on the reel, the pope drum and the web tension. The forth disturbance occurs when the spool makes contact with the rails, (h). The disturbance which occurs has an effect on the reel, the pope drum and the sections before. The fifth disturbance occurs when the primary arms are disengaged and the secondary arms are engaged, (i).

VARIABLES TO CHARACTERIZE THE DISTURBANCES

The synopsis of the reel change procedure pointed to disturbances on five occasions.

The primary reason for the first disturbance is the change of the web tension when the paper is shifted. In the next three cases there is a change of the angular velocity of the reel which is the primary reason for the disturbance. The primary cause of the disturbance in the last case is a change of the nip force.

This means that the angular velocity of the reel, the web tension and the nip load are the main variables. In practice the changes of the nip load are influenced by various design parameters of the pope reeler. The angular velocity of the reel, and the web tension are general variables. To characterize the disturbances the rotation speed and the web tension will be used in this study. The variation of the current to the drives which is proportional to the torque is used to characterize the interaction between the disturbances at the reel and the calender and dryer sections. Figure 5 shows a sketch of the angular velocity of the machine reel during the change procedure and the marks which are used to describe the position of the reel and the disturbances.

MEASUREMENT OF DISTURBANCES

Measurement System

A PC-based measurement system was developed to do measurements on paper machines. The angular velocities were measured with digital pulse encoders, the web tensions with analog force transducers. A new system was developed to measure the angular velocity of the machine reel. It consists of a transducer mounted on the end of the spool and a system with infrared transmitters and receivers to send the data to the PC-system. The transducer is based on an ordinary pulse encoder with 1000 pulses/rev. which is held in position by a well damped pendulum. The pendulum gives the transducer a defined natural frequency which is eliminated by a digital FIR filter. The data from the different transducers were stored in a common binary file. Figure 6 shows the components of the system. The time between a number of pulses is measured to determine the rotation speed. The resolution of the time measurement system is 50 ns. This means that the number of pulses per revolution and the angular velocity influence the sample rate and the resolution. The number of pulses per revolution which are measured is controlled by the software. Usually the rotation speed of the machine reel varies between 10 and 1 revolution/s. Figure 7 shows the corresponding available range of sample rate and resolution.

To measure the angular velocity of the rollers and the pope drum the ordinary pulse encoders of the paper machine with 1000 pulses/rev. were used.

Angular Velocity and Web Tension

Figure 8 shows the measured relative velocity difference of the pope drum, the rollers of the calender and the dryer during the reel change sequence. The figure also shows the rotation speed of the machine reel. The pope drum is controlled by a constant torque. The dryer is controlled by draw and the calender is controlled by draw and web tension. The measurement shows that the velocity of the dryer section is not influenced by the disturbances at the pope drum. Figure 9 shows the current of the calender drive and the web tensions of the pope and the calender sections. The current of the calender drive varies to keep the web tension constant in the calender section but at the same time contributes to amplify the disturbances at the pope drum.

Simulation of the Reel Change

The mass moment of inertia of the machine reel is composed of two parts, one from the paper and one from the reel spool.

$J_m = J_w + J_s$ (1)

The angular winding velocity and the mass moment of inertia change as a function of time during the winding. The mass moment absorbed by the inertia of the reel is:

$$M_m = J_m \cdot \frac{d\omega}{dt} + \frac{dJ_m}{dt} \cdot \omega \tag{2}$$

If the machine reel is driven by a nip there is a tangential force corresponding to M_m

$$F_m = \frac{M_m}{r} \tag{3}$$

In practice F_m is a force which has to be transmitted in the nip between the reel and the pope drum. To determine F_m is a way to characterize the disturbances during the reel change procedure.

The position of the reel is described by an angle φ and

The expression to the calculate the angular velocity of the reel is:

$$\omega = \frac{V_p - \varphi \cdot r_p}{r} \tag{4}$$

To calculate ω it is essential to know $\dot{\varphi}$. A first approximation is to use linear functions to describe the angular velocity $\dot{\varphi}$. Figure 10 shows the shape of $\dot{\varphi}$.

The winding on a new spool starts at the position 1 and the angle φ_1. When the full reel has been moved away, the new reel can be transferred down along the periphery of the pope drum with a certain angle velocity $\dot{\varphi}(t)$. When the reel reaches position 2, described by the angle φ_2, it is stopped.

The increase of φ is: $\varphi_2 - \varphi_1 = \Delta\varphi$.

The parameters used to analyze the transfer of the reel are:

$$\text{Start of transfer} = t_1$$
$$\text{Transfer time} = t_4 - t_1$$
$$\text{Ramp time 1} = t_2 - t_1$$
$$\text{Ramp time 2} = t_4 - t_3$$

The angular velocity is:

$$\dot{\varphi} = \begin{cases} c_1(t-t_1), & t \in (t_1, t_2) \\ c_2, & t \in (t_2, t_3) \\ c_2 + c_3(t-t_3), & t \in (t_3, t_4) \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

There are three equations that the constants c_1, c_2 and c_3 must satisfy:

$$\int_{t_1}^{t_4} \dot{\varphi}\, dt = \Delta\varphi \tag{6}$$

$$c_1(t_2 - t_1) = c_2 \Rightarrow c_1 = \frac{c_2}{(t_2 - t_1)} \tag{7}$$

$$c_3(t_4 - t_3) = -c_2 \Rightarrow c_3 = \frac{-c_2}{(t_4 - t_3)} \tag{8}$$

Equation (6) gives:

$$\int_{t_1}^{t_4} \dot{\varphi}\, dt = c_2 \underbrace{\left[\frac{t_2 - t_1}{2} + (t_3 - t_2) + \frac{t_4 - t_3}{2}\right]}_{k} = \Delta\varphi \Rightarrow c_2 = \frac{\Delta\varphi}{k} \tag{9}$$

Equations (7) and (8) give:

$$c_1 = \frac{\Delta\varphi}{k(t_2 - t_1)} \tag{10}$$

$$c_3 = \frac{-\Delta\varphi}{k(t_4 - t_3)} \tag{11}$$

With this expressions the angular winding velocity of the reel and F_m can be calculated. The winding is assumed ideal which means a constant thickness of the web and no slippage between layers in the reel or between the reel and the drum.

If φ is constant J_m and ω change continuously. Figure 11 shows how F_m varies as a function of time when a reel is wound with a paper with high and low thickness respectively. Near the spool F_m is positive otherwise negative. A positive value of F_m means that the reel gives the pope drum a force to increase the speed. F_m increases with J_m, machine speed, web thickness and grammage of the web and decreases with the radius of the spool.

During the transfer from the starting position down to the rail, the reel has a lower angular winding velocity compared to winding at a stationary position. Figure 12 shows an example of a simulation with data corresponding to a modern paper machine. Disturbances occur when the transfer starts and stop. Factors influencing the disturbances are J_m, $\Delta\varphi$, machine speed, transfer time, diameter of the pope drum, diameter of the spool, thickness and grammage of the web. Most important factors are the ramp times. Short ramp time means high F_m values due to the large spool on paper machines.

Comparison Between Simulation and Measurement

To compare the measured and calculated values of the angular winding velocity of the machine reel it is assumed that there is no slippage between the paper layers or between the machine reel and the pope drum. Figure 13 shows the variation of angular winding velocity compared to the ideal winding in a stationary position without disturbances. The four disturbances in the figure are marked according to the reel change procedure discussed in Figure 4 and 5. The first disturbance occurs when the predrive system is disconnected and the spool is moved to the surface of the pope drum. The second disturbance occurs when the winding starts on the spool. During the transfer the measured values become successively less than the values from the model. The reason is that the nip load is decreasing. When the transfer is completed the angular winding velocity of the measured reel is about 0.1 % smaller compared to the model. In this case it corresponds to an increase of the web thickness of about 1 μm.

The change of the speed of the pope drum at the start and stop of the transfer was very rapid, see Figure 14 and Figure 15. This means that the tangential force from the machine reel must be considerable at these points which is the reason for the great disturbances of the web tension.

In this example there are clearly two reasons for the disturbances and the variations in the web tension and velocities. The fast change of angular velocity during the transfer and the uncertain control of the nip load.

RESULTS WITH MODIFIED CONTROL OF THE REEL CHANGE

The paper machine was modified to be able to control the nip load and the angular velocity of the primary and secondary arms. Force transducers were installed to measure the nip loads and position transducers to measure the position of the primary and secondary arms, see Figure 3. Servo valves were installed to control the hydraulic cylinders in closed loop circuits.

Figure 16 shows how the angle of the primary arm varied during the reel change sequence. Figure 17 and Figure 18 show the speed variations and the variation in the web tensions. The disturbances are concentrated to a short period just before and after the shift of the paper web from the full reel to the spool. To compare the disturbances before and after the modification of the control system this period is excluded. Figure 19 shows a plot of the variations of the speed of the pope drum and the web tension before the modification. Figure 20 shows the corresponding plot after the modification of the control of the reel change. The draw and the web tension control of the paper machine are the same. The only difference is the control of the positions of the primary and secondary arms and the nip load between the reel and the pope drum. After the modification the variations of speed and web tension do not increase during the reel change period.

CONCLUSION

Characteristic disturbances have been found during the reel change period by comparing simulation of ideal winding and measurements of angular winding velocity. The divergence between measurement and simulation provides the possibility of analyzing the mechanisms behind the disturbances.

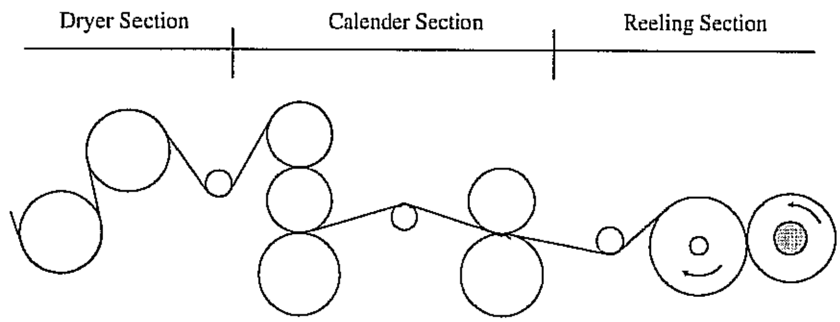


Figure 1 Sections of a Papermaking Machine

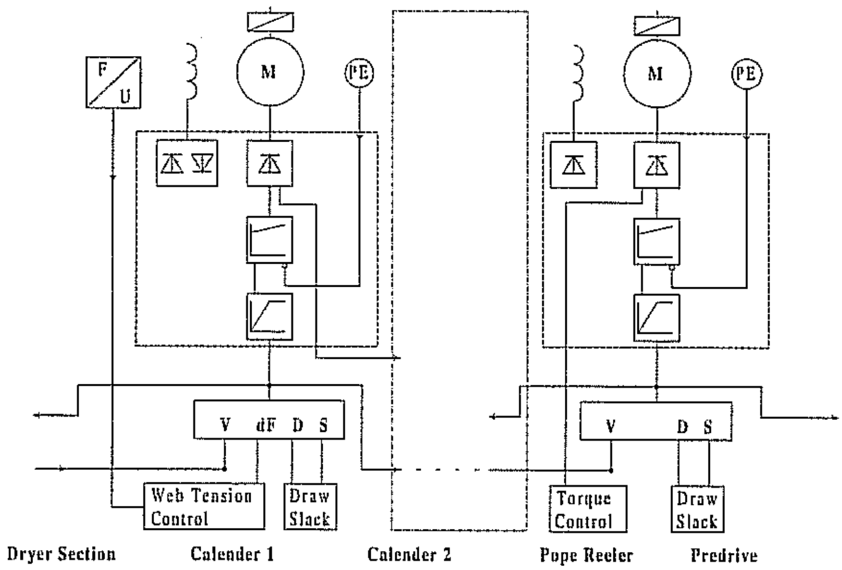


Figure 2 Draw Control

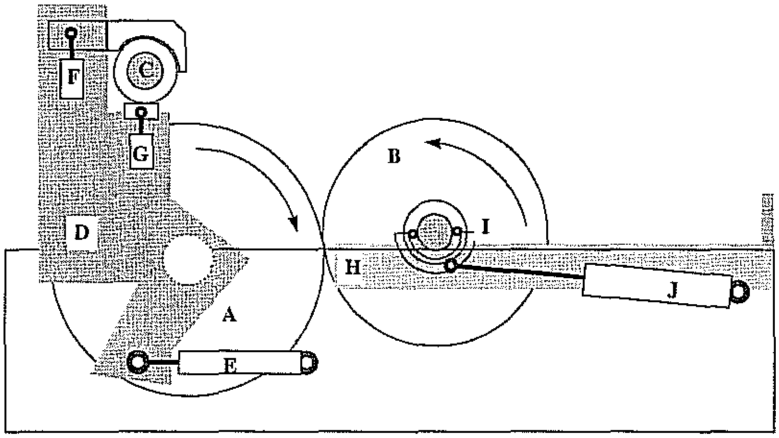


Figure 3 Pope Reeler. Pope Drum A, Machine Reel B, Spool C, Primary Arm D, Positioning Cylinder E, Load Cylinder F, Unload Cylinder G, Rail H, Secondary Arm I and Positioning Cylinder J. In the Modified Reeler Load Cells were installed at F, G and I. Position Transducers at E and J.

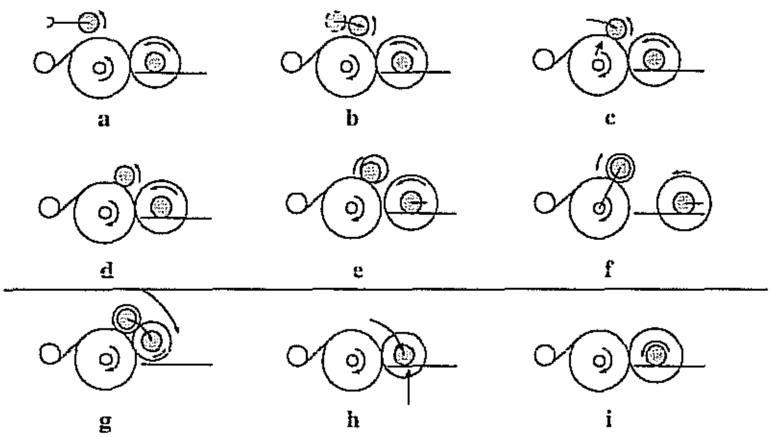


Figure 4 Steps of the Reel Change Procedure.
a: Spool Predrive, b: Predive Disengages, c: Contact Between Spool and Drum, d: Stand-by, e: Winding Starts on Spool, f: Winding at Stationary Position, g: Transfer Starts, h: Contact Between Spool and Rail and i: Nip Load Control Shifts from Primary to Secondary Arms

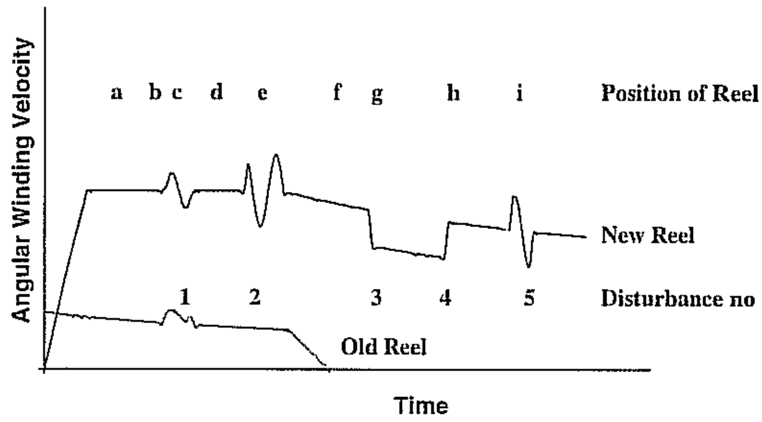


Figure 5 Angular Velocity of the Reels During the Change Period.
Disturbances: 1: Contact Spool-Drum, 2: Web skifts, 3: Transfer starts, 4: Transfer stops, 5: Nip Load Exchange. Positions: a-i According to Figure 4.

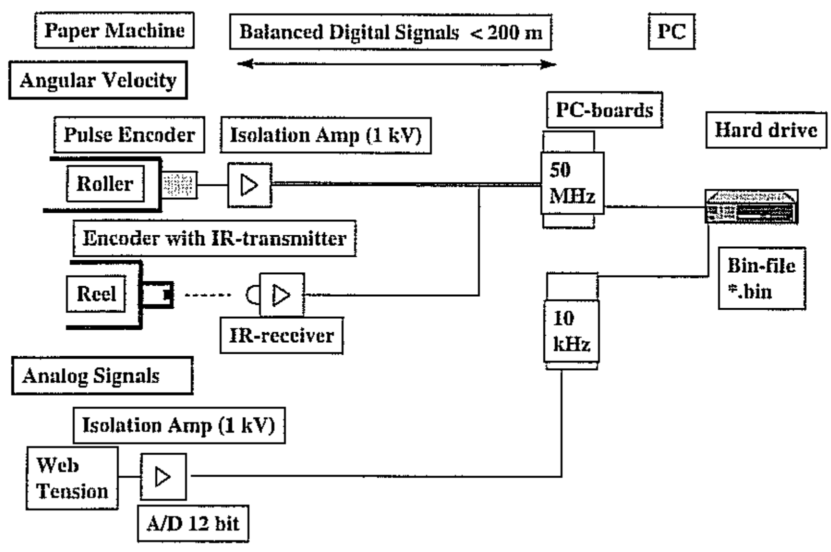


Figure 6 Measurement System.

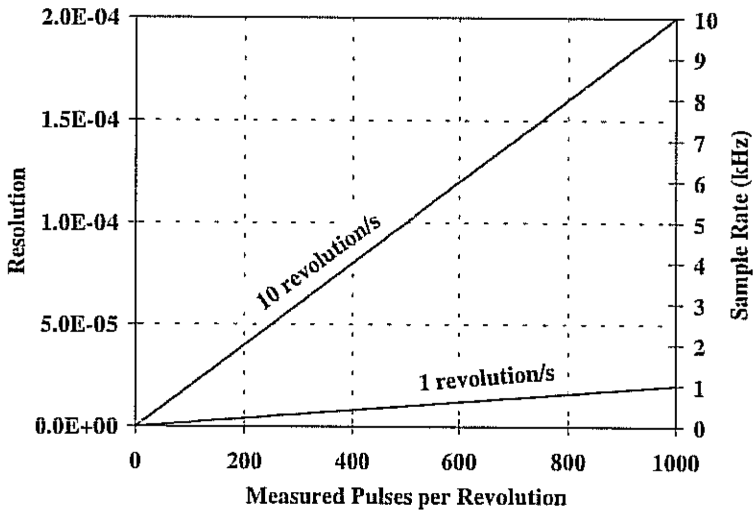


Figure 7 Sample Rate and Resolution as a Function of the measured Number of Pulses per Revolution.

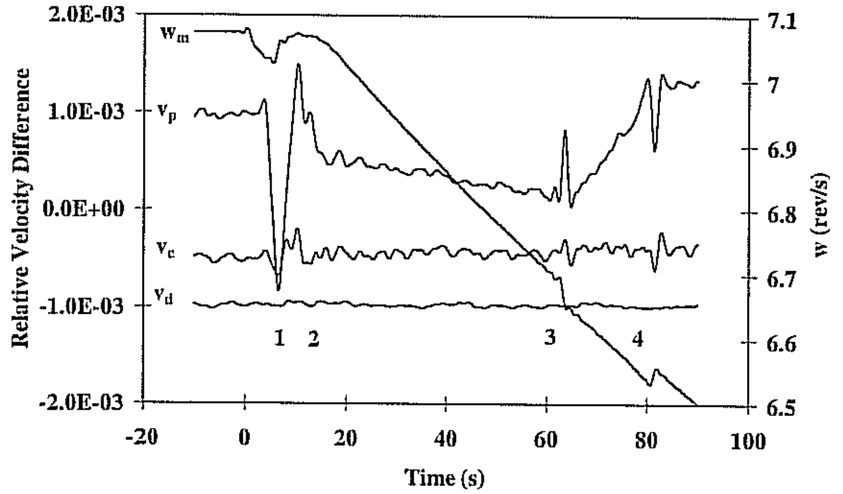


Figure 8 Variation of Veloity during the Reel Change Period. Positions marked according to Figure 5.
Reference Velocity is the Machine Speed 17 m/s.

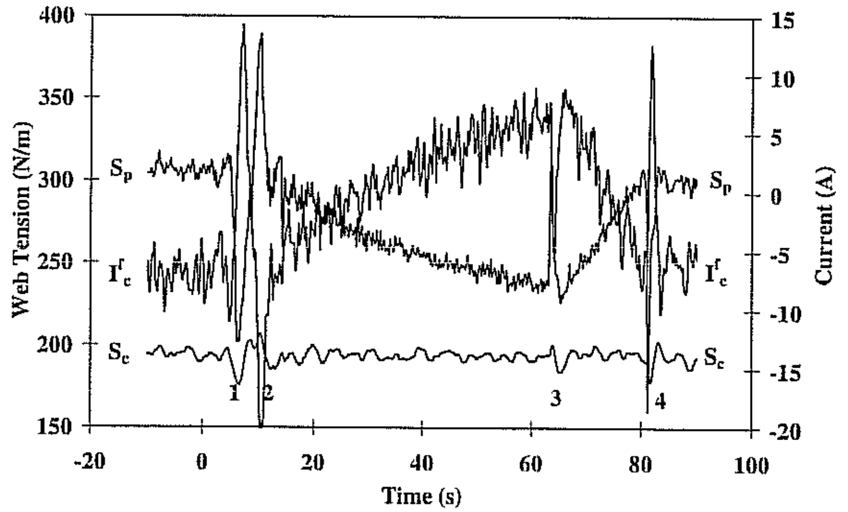


Figure 9 Variations of Web Tensions and Current controlling the Torque of the Calender Rollers during the Reel Change Period. Positions marked according to Figure 5.

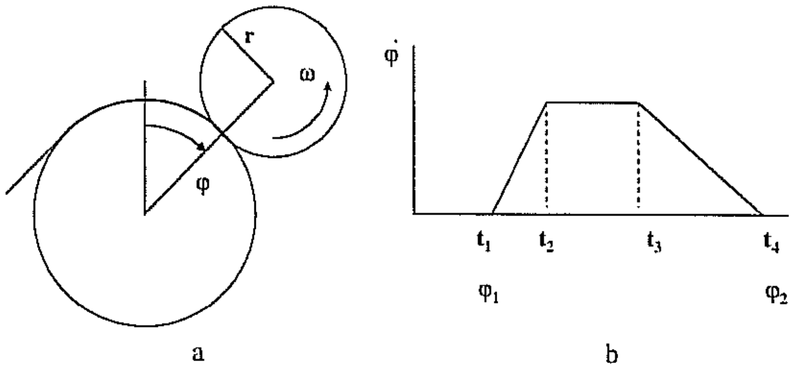


Figure 10 Geometry of the Pope Drum and the Reel a and the Parameters determining the Angle Velocity b.

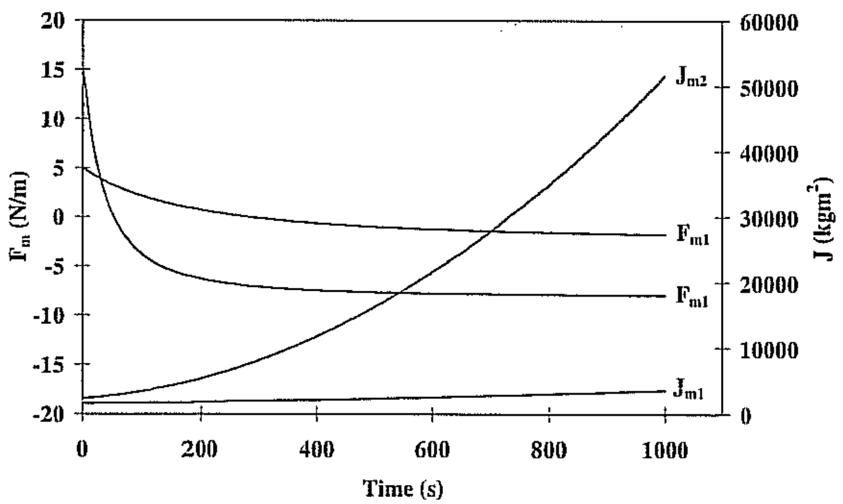


Figure 11 Simulation of Ideal Winding in Stationary Position F_m and J_m as a Function of Time. Parameters of Reel 1: b=8.5 m, h=50μm, G=35 g/m^2, V_p=25 m/s, M_s=10000 kg, d_s=0.75 m. Parameters of Reel 2: b= 8.5 m, h=400μm, G=250 g/m^2, V_p=10 m/s, M_s=20000 kg, d_s=0.75 m

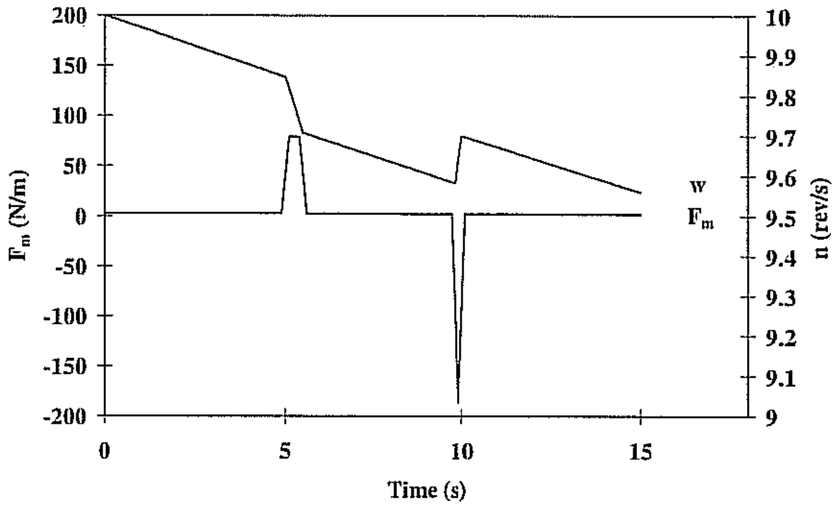
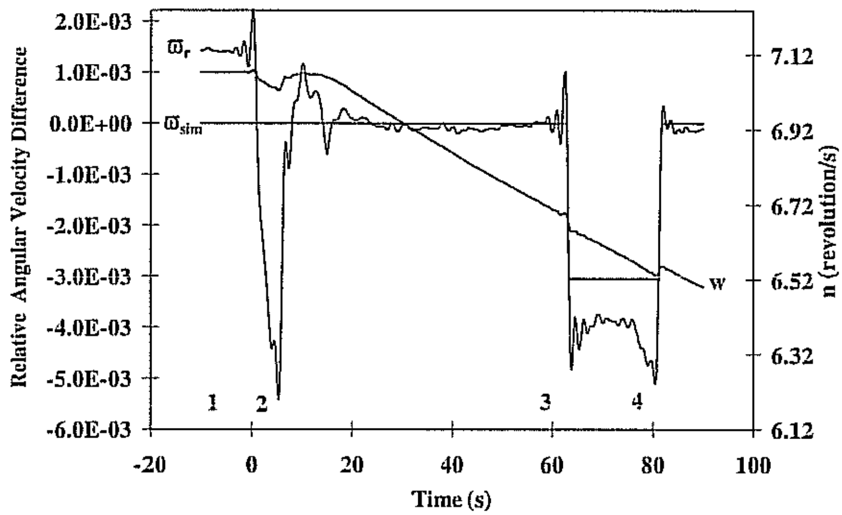


Figure 12 Simulation of Ideal Winding including Transfer. F_m and w as a Function of Time. Parameters: b=8 m, h=100 μm, G=150 g/m^2, V_p=20 m/s, M_s=10000 kg, d_s=0.64 m, d_p=1.5 m, t_2-t_1=0.5 s, t_4-t_3=0.2 s and t_4-t_1=5



sec.

Figure 13 Comparison of Predicted and Measured Variation of Angular Velocity. Positions marked according to Figure 5. V_{ref}=17 m/s

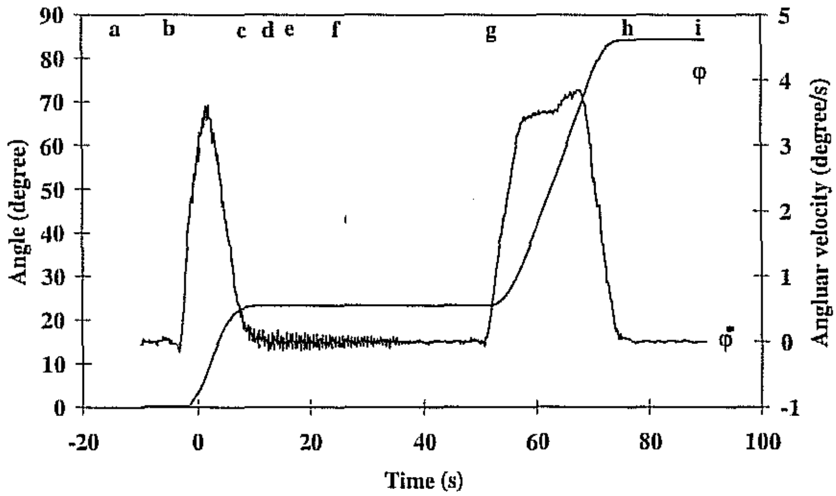


Figure 16 Angle and Angle Velocity measured after Installation of Closed Loop Control. Positions marked according to Figure 5.

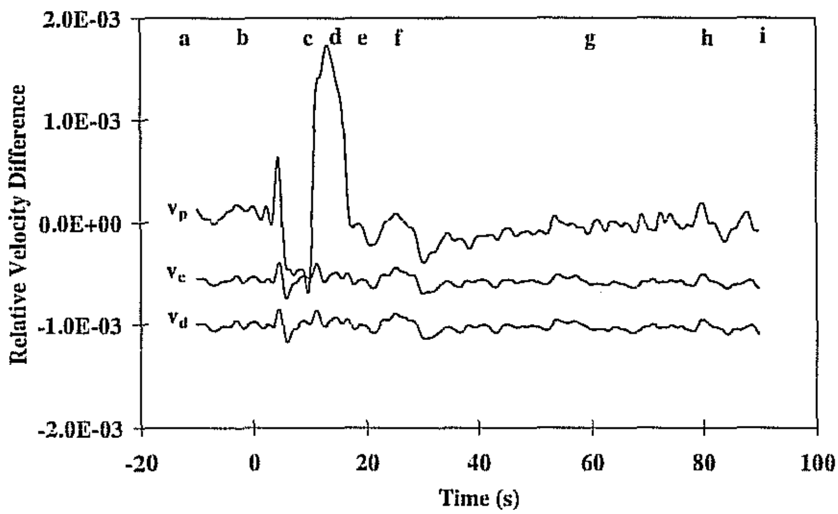


Figure 17 Relative Velocity Differences during the Reel Change Period. Modified System. Positions marked according to Figure 5. V_{ref}=17 m/s

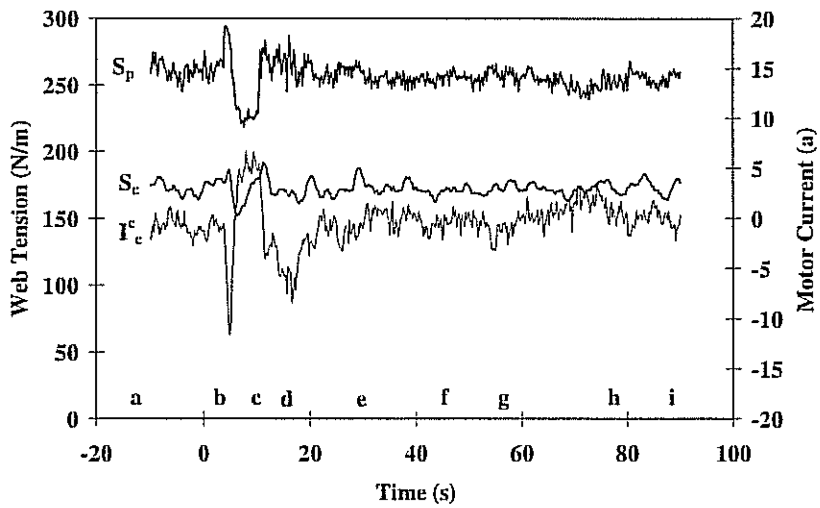


Figure 18 Web Tensions and Variation of Current Controlling the Torque of the Calender Rollers during the Reel Change Period. Modified System. Positions marked according to Figure 5.

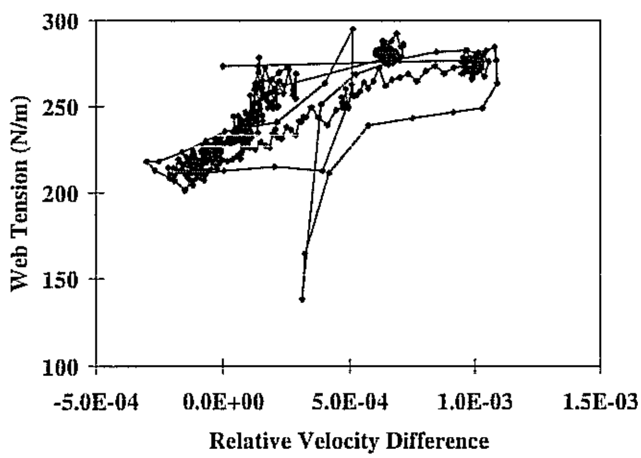


Figure 19 Plot of Variations of the Velocity of the Pope Drum and the Web Tension during the Reel Change Period. Data 5 sec before and 10sec after the Winding starts on the new Spool are excluded. Original System. Reference Velocity 17 m/s.

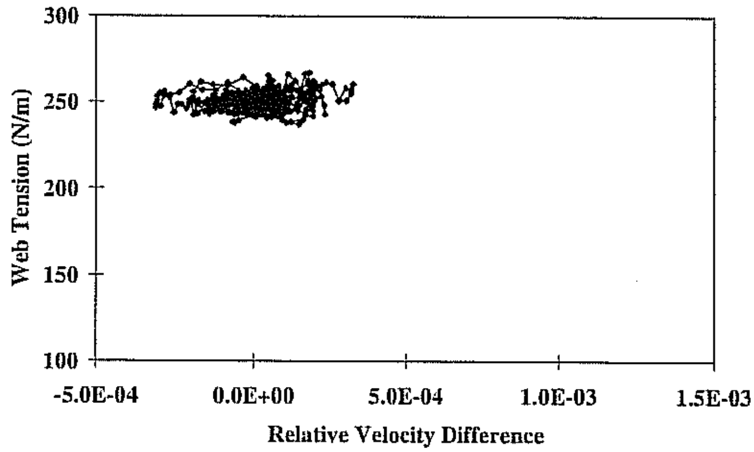


Figure 20 Plot of Variations of the Speed of the Pope Drum and the Web Tension during the Reel Change Period. Data 5 sec before and 10 sec after the Winding starts on the new Spool are excluded. Modified System. Reference Velocity 17 m/s.