MEASUREMENT AND CONTROL OF THE TENSION DISTRIBUTION ACROSS THE WEB IN A NEWSPAPER PRINTING PRESS

L. G. Eriksson

Swedish Newsprint Research Centre

Djursholm, Sweden

ABSTRACT

A bending moment in a newsprint web caused by unevenly distributed tension across the web leads to disturbances in the production. Measurements in a printing press during newspaper production showed large variations in the bending moment. The cause was found to be variations in mechanical properties of the paper, variations induced by the printing process e.g. reel changes, variable press speed and different amounts of fountain solution in different parts of the web. It has been found that the moment can be eliminated by an adjustment of the angle of the axis of a roller in the press.

A control system has been developed to eliminate the moment of the web in the printing press. The bending moment and the forces in the machine and cross-machine directions are measured by a roller mounted on load cells. The same roller can be used both as a sensor and as the controlling adjustable roller.

In the first section of this paper, the manner in which adjustments of a control roller will influence the stresses in the paper and the stability of the web has been theoretically studied. Based on the Timoshenko beam model, a mathematical model of the web has been established. Numerical calculations of forces, moments and lateral displacements in the web have to be made. The model is formulated in such a way that the stress characteristics in a web span are governed by only two dimensionless parameters, K_SL and g. These parameters depend on the tension in the web, the free length and width of the web span and the bending and shear stiffness of the web.

The model can also be used to draw conclusions about the optimum design of the web lead when a control roller is to be installed in a printing press. The lengths of the spans on both sides of the control roller and the wrap angle can be changed to diminish the lateral displacement downstream of the control roller to negligible values. The design of the web lead must also fulfil the condition that the load on the upstream span from an adjustment of the control roller is smaller than the load on the downstream span. Measurements in the laboratory with 300 mm wide webs

confirmed these theoretical results. It was also experimentally found possible to change the moment in the web without any permanent lateral displacement of the web at the rollers downstream of the control roller.

In the second section of this paper, the development of a closed loop control of the moment in a newspaper printing press based on measured values of the bending moment, the web tension and the web speed is described. The largest disturbances occurred during the automatic reel changes, especially when two papers subjected to a flying splice had different elastic properties. The time constant of the control-roller response was chosen to be of the same order as the rise time of the change of the moment from the automatic reel change. Recorded data showed that the control system was able to suppress the fast variations of the moment which occur during the automatic reel change at full press speed.

Analysis of data from a large number of printed reels also showed that the correction signal from the control system reflected inherent properties of the reels. The device can therefore be used to map paper and reel properties.

Several hundreds of reels have been printed in a production press with the automatic control system in operation. A considerable improvement in runnability has been observed.

NOMENCLATURE

A	=	as a subscript, roller A
Cr	=	as a subscript, critical value
A	=	cross-sectional area of the web, m^2
E	=	elasticity modul, (Young's modulus), N/m^2
Eh	=	tension stiffness, N/m
EI	=	bending stiffness of a web, Nm^2
F	=	force, N
G	=	shear modulus, N/m^2
g	=	$\frac{nS}{Gh}$, dimensionless parameter
Gh	=	shear stiffness, N/m
h	=	thickness, m
I	=	$hw^3/12$, m^4
K_s^2	=	$T/EI(1+g)$, m^{-2}
K_sL	=	a dimensionless parameter
L	=	length of a free span of a web, m
l	=	running length of web, m
M	=	bending moment, Nm
N	=	shear force, N
n	=	averaging factor
S	=	web tension, N/m
T	=	total force in a web, N
t	=	time, s
u	=	position of the shaft end of the control roller, mm
v	=	velocity of the web, m/s
W	=	web width, m
X, Y	=	Cartesian coordinates

X	=	direction of web travel
Y	=	cross direction
Y^I	=	$\frac{dy}{dx}$
Y^{II}	=	$\frac{dy^2}{dx^2}$
b	=	length of pivot axis, m
ν	=	Poisson's constant
Φ	=	angle between the web and X-axis
Θ	=	angle between control roller and Y-axis
φ	=	angle between the ingoing web and the control-roller plane
ψ	=	angle between the outgoing web and the control-roller plane

INTRODUCTION

Newspapers are everyday products which for their production demand large quantities of newsprint. The total world production of newsprint is 33 million tons per annum, which means a turnover of about 100 000 tons of newsprint every day. A modern newsprint machine runs at more than 20 m/s (1 200 m/min) and produces more than 600 tons standard newsprint in 24 hours. Knowledge of web-handling phenomena are very useful in the production and printing of newsprint all the way from the headbox of the paper machine to the folder of the printing press.

Newspapers are produced in large, fast running presses, which has led to a concentration of the printing operation to plants with a high degree of automation. The high investment costs of modern newspaper presses makes it necessary to use the presses to produce various products and to reach a high availability. This means that the printing press must be designed to meet different demands which, unfortunately, increases the complexibility of the system. These fast running machines increase the demand for the stability of the running web and on the quality of the newsprint itself. One expression for the quality of the whole system is the web-break frequency. Today, many pressrooms have reduced the web-break frequency to a few breaks per 1000 printed reels. However, the large economic consequences of a web break or a badly running web means that the challenge to eliminate the web-breaks is still a most important area for R & D efforts.

The productivity and quality of the final product depend on a stable web transport. There is a strong relationship between the stability of the web and the level of and variation in web tension. The optimum web-tension level in printing presses is found to be between 100 and 300 N/m. A higher web-tension level improves the stability of the web, but often results in an unacceptable web-break frequency, Eriksson [1]. The breaking strength of newsprint measured on small samples (100 mm x 50 mm) is however 2000 N/m or more in the machine direction and about 800 N/m in the cross-machine direction.

There is an obvious difference between the strength necessary to build into the paper and the average web tension which can be used in practice in a printing press . To narrow this gap without loss of productivity is of great economic importance. It can only be done through a better understanding of the dynamic situation in a press and through the development of new techniques to handle newsprint webs.

In practice, the web tension in a printing press varies across the web. The variation can be caused by variations in, for example, grammage, thickness, moisture content and fibre orientation. In addition, in offset printing, the dominant process in newspaper printing , the paper takes up fountain solution of around 0.5 g/m^2 in each printing nip, which changes the dimensions and elastic properties of the web when it is running through the press, Trollsås and Larsson [2] and Bristow [3].

Newsprint is a brittle material when dry but tough if the moisture content is high. The shipping rolls have a moisture content of about 9 % which gives the web semi-brittle properites when it is running in a printing press. According to the theory of fracture mechanics, the shortest flaw at a given web tension which can cause a web break close to the edge is only half the size of that required in the center of the web. This means that the stresses at the edges of the newsprint webs are the most important positions to monitor and control, Eriksson and Viglund [4] and Bergström and King [5]. In this work we have found from a theoretical study that it is possible to both monitor and control the paper web by an adjustable roller. Such a roller has been constructed with its appropriate controlling electronics and tested in a production printing press.

THEORETICAL ANALYSIS

In order to find whether it is possible to give a running paper web a web tension free from bending moment without losing control of the lateral position of the web in the press, a theoretical model has been developed and analysed.

Theoretical model

To analyse the bending moment and the forces which are created in a running web by an adjustable roller, the elementary theory of beams according to Timoshenko is used as a starting point [6].

The material is assumed to be homogeneous, isotropic and elastic. The symbols used in the model are shown in Figure 1.

The bending moments and the shear forces are given by the equations

$$M = - EI\, Y^{II} \quad (1)$$

$$N = - EI\, Y^{III} \quad (2)$$

where Y is the deflection of the elastic curve of the web.

For small deflections the assumption can be made that the normal stress in all parts of the web is positive or zero. The bending moment is therefore restricted to

$$\left| M \right| < M_{Cr} = \frac{TW}{6} \quad (3)$$

The elastic line of the web shall satisfy a fourth order differential equation, Timoshenko [6].

$$Y^{IV} - K_s^2\, Y^{II} = 0 \quad (4)$$

where K_s and g are dimensionless parameters given by:

$$K_s^2 = \frac{T}{EI(1+g)} \qquad (5)$$

$$g = \frac{nS}{Gh} \qquad (6)$$

The parameter K_s is influenced by the web tension, S, and the bending stiffness EI. The term g depends on the distribution of the shear stress in the web. This gives a sufficiently good approximation to be able to study the influence of the shear deflection on the forces and the displacement of the web.

The general solution of equation (4) is

$$Y = C_1 \text{ Sinh } K_s X + C_2 \text{ Cosh } K_s X + C_3 X + C_4 \qquad (7)$$

Where the constants C_1 - C_4 depend on the boundary conditions. In a simple situation like that in Figure 1 the boundary conditions are

$$Y_A = 0 \qquad (8)$$

$$Y_A{}^I = 0 \qquad (9)$$

$$Y_B{}^I = \Phi_B = \Theta_B \qquad (10)$$

$$M_B = 0 \qquad (11)$$

The boundary condition expressed in equation (11) has been verified theoretically by Brandenburg [7] and experimentally by Shelton [8]. The solution for the web span AB is

$$Y = \Phi_B \frac{(1+g)\,(\text{Sinh } K_s L\,(\text{Cosh } K_s X - 1) - \text{Cosh } K_s L \text{ Sinh } K_s X)}{K_s((1+2g) \text{ Cosh } K_s L - (1+g))} + \frac{F_B\,(1-2g)\, X \text{ Cosh } K_s L}{(1-2g) \text{ Cosh } K_s L - (1+g)} \qquad (12)$$

For small deflections, the solution gives

$$N_A = T\Phi_B f_1 \qquad (13)$$

$$N_B = T\Phi_B f_2 \qquad (14)$$

$$M_A = - T\Phi_B L f_3 \qquad (15)$$

$$Y_B = \Phi_B L f_4 \qquad (16)$$

$$\Phi_{cr} = \left(\frac{W}{L}\right) f_5 \qquad (17)$$

where f_1 ... f_5 are all dimensionless functions. The boundary conditions for the situation described in Figure 1 give the following expressions for the functions f_1 ... f_5.

$$f_1 = \frac{1}{(1+2g)\ \mathrm{Cosh}\ K_sL - (1+g)} \qquad (18)$$

$$f_2 = f_1 \mathrm{Cosh}\ K_sL \qquad (19)$$

$$f_3 = \frac{f_1}{K_sL} \mathrm{Sinh}\ K_sL \qquad (20)$$

$$f_4 = (1+2g)\ f_2 - (1+g)\ f_3 \qquad (21)$$

$$f_5 = \frac{1}{6\ f_3} \qquad (22)$$

The solution for the web span BC is the same as that for the span AB if the origin of the coordinates is moved to the roller B, Φ_B is replaced by $-\Phi_B$ and the term $X\Phi_B$ is added to the displacement, Y. In this way a mathematical model of a running web can be constructed by the addition of separate sections provided that no moments are transferred over the rollers.

Influence of Paper Properties and Press Parameters on the Form of the Paper Web

The deflection of the web and the forces in the web depend only on the two parameters K_sL and g. The characteristic range of variation of the parameter K_sL in different production lines using newsprint webs, is drawn in Figure 2. The normal range of variation of g can be estimated to be between 0.005 and 0.02.

In this work we wish to find the relation between the angle of a slightly adjusted control roller and the behaviour of the paper web. Numerical calculations show that there is a very sensitive relationship between the angle of the roller and the behaviour of the paper web as a function of the two parameters K_sL and g. Examples of the calculations are shown in Figure 3.

In a printing press, for example, a small adjustment of the roller creates strong forces in the web when the parameter K_sL is small, Figure 3a - 3c. This sensitivity decreases however when the value of K_sL becomes higher. This also means that spans in the press with low K_sL values are critical sections where the precision of alignment must be very high.

It is also obvious from Figure 3 that the parameter g influences the situation. Generally, an increase in the value of g increases the deformation but decreases the forces in the web. Again, the largest consequences are found when the K_sL value is small. Short distances between consecutive rollers consequently again give critical sections in a printing press.

EXPERIMENTAL TESTS OF THE THEORY

Test Equipment

To measure bending moments and shear forces, a special measuring device has been built, the principle of which is outlined in Figure 4. The shafts of the measuring roller are carried by low friction, ball bushings. The roller is held by three load cells which take up the forces from the web. The device is sensitive to variations in the tension at the edges of the web. In order also to reduce the web-tension disturbances in the printing press, a control system has been developed based on the measuring roller as a sensor. The main component parts of the control system are shown in Figure 5. In the control system, the same roller is used both as a sensor and as a correcting device to adjust the web-tension moment to zero. This device is called the control roller.

A stepping motor is used to change the angle of the control roller. Analog transducers are used to measure the press speed, the roller angle, the shear force, the web tension in the machine direction and the bending moment on the roller induced by the web tension. The signals from the sensors are handled by a microcomputer, which controls the stepping motor.

The control-roller system has been built as a separate unit which is mounted on the press frame. The mechanical design is shown in Figures 6 and 7. The control roller has dead shafts made of annealed steel. The shafts are carried by ball bushings. The construction of the bushings allows the angle of the roller to be adjusted ± 0.5 degrees which is the range needed for the control.

The right-hand shaft end is connected to a load cell to measure the shear force. The other shaft end is mounted on a linear ball bearing, which is moved by the stepping motor to set the roller angle. The roller with all the bearings is mounted on two magneto-elastic load cells. These load cells provide the signals for measurement of the web tension and the bending moment on the roller.

A keyboard is connected to the microprocessor to communicate with the system. The control system has been designed to operate in three different modes:

Measurement mode: The control roller is mechanically locked and is used only to measure the forces and the moment of the web.

Manual control mode: The roller angle is controlled by a manual control unit.

Automatic control mode: Closed loop control. The control of the roller angle is based on the signals from the sensors measuring the bending moment on the roller, the web tension and the web speed.

Measurement of web-tension profiles

Web-tension profiles were measured separately to check the influence of the control roller on the stress of the web.

To measure the profiles an electro-acoustic transducer with 4 cm measuring gap was moved across the web. The transducer is described by Eriksson [9]. Figure 8 shows a characteristic result. If the adjustment of the roller angle is small, the change in web tension is linear across the web according to the theory. If the angle is increased to larger values a redistribution of the tension takes place due to loss of traction on the control roller. The conclusion is that the change in web-tension profile is linear if $|\Theta| < \Theta_{cr}$

Measurement of Responses to Adjustments of the Control-Roller Angle

The dynamic response of the paper web to an incremental change in the angle of the control roller was determined by moving one shaft end u horizontally, Figure 9. The angle Θ of the roller is, according to Figure 9, given by:

$$\Theta = \frac{u}{b} \tag{23}$$

The forces and bending moments in two consecutive web spans were measured by three measuring rollers.

The responses to a step change of the angle of the control roller are shown in Figure 10. At the time $t = 0$, a step is applied to the control roller B. As a consequence, the control roller creates bending moments in the upstream and downstream spans of the web. A further consequence is that the web is gradually displaced in the Y-direction at the roller B and at the roller C. When the web is finally stationary in the Y-direction, the moment is constant at the roller A and zero at the upstream side of the roller B. At roller C there is only a transient pulse of moment left which propagates forward in the system. The time constants of the responses are proportional to the lengths of the spans of the web and inversely proportional to the speed of the web, Figure 11. These results fully agree with the boundary conditions of the model expressed in equation (11).

Analysis of the Function of the Control-Roller System in a Printing Press

The objective of the control-roller system is to control the bending moment on a web in a printing press automatically. The function of the control system depends on the web lead. Figure 12 shows the ordinary web lead ADE in the printing press used for the test program. With the control roller installed, two alternatives for the web lead are ACD and ABCD. The web lead ABCD requires an extra pipe roller B to be mounted on the press frame.

A series of tests have been performed in the laboratory to examine whether the extra pipe roller B is necessary for the function of the system. In the experiments, the web lead was identical to that in the printing press except that the width of the web was 300 mm instead of 1640 mm. Because of the narrow web, the deviation of the control roller must be enlarged to achieve the same responses as for a web of full width. Figure 13 shows the main results of the tests. Without the roller B, the web is permanently displaced at the roller D if the angle of the control roller is changed. If the roller B is included in the web lead, the displacements in the spans BC and CD are approximately the same but of opposite sign. A change in the roller angle consequently gives only a transient disturbance of the lateral position of the web at the roller D. The duration of the disturbance is of the same order as the transport time of the web from roller B to roller D. The tests also show that the moment in the web, M_C, increases when the angle of wrap on the control roller is increased. As a result of the laboratory tests, the extra pipe roller was installed in the printing press to diminish the lateral displacement in position D and to increase the bending moment in position C.

In a full scale printing press, the control system influences the moment upstream as well as downstream of the control roller. In the closed loop control mode, the moment of the control roller on the web in the upstream span must be the same or smaller than the moment in the downstream span, otherwise the control system overcompensates the disturbances of the bending moment. To determine whether a specific web lead is appropriate for closed loop control, the theoretical model can be used. The width of the web and the web geometry, the lengths of the spans and the angles φ and ψ, Figure 9, all affect the parameters K_SL and g, which govern the moments and the displacements of the different spans of the web. The web lead in the printing press and the symbols used for the theoretical analysis are outlined in Figure 14. The parameters of the web for this full scale test and results of the theoretical calculations are shown in Table 1.

The first case, Table 1, is a pure bending of the web, without shear deflection. In the second and third cases, the deflection of the web is caused by both bending moments and shear forces. The third case represents an upper limit of the shear deflection that can be assumed in a newsprint web with anisotropic properties.

Experimental tests of the outcome of the theoretical model for this example have been made. Measurements were carried out in the printing press to determine how different roller angles change the moment on the control roller at different speeds of the web. The bending moment M_C at zero speed of the web was determined to be 90·u Nm if u is measured in mm. When the press was running, the bending moment was reduced to 40·u Nm. At zero speed, the two spans on either side of the control roller contribute to the measured moment. In the running web, there is no contribution from the entering span hence the control roller is exposed to a lower bending moment. This agrees well with the recorded response of M_B shown in Figure 10. One important consequence of the configuration ABCD is that the bending moment in the span BC is less than the bending moment in the span CD, which was one requirement for a stable closed loop control in the printing press.

The lateral displacement at the roller D is not more than $\pm$ 0.1 mm and is in practice negligible. If the displacement $|u| < 2$ mm, the bending moment M is a linear function of u. In practice, corrections larger than $u = \pm 1$ mm are seldom needed to eliminate disturbances in the bending moment in the web. This means that the control system works within the linear range of the response of the paper web. Due to the asymmetric location of the pivot point, the control roller also has a transient influence on the total web tension in the machine direction. The greatest change in the web tension occurs at zero speed. For example, a displacement u = 1 mm changes the web tension about 10 N/m.

EXPERIENCE FROM TESTS IN A PRODUCTION PRINTING PRESS

The control system has been working for several months in the production of newspapers at Dagens Nyheter in Stockholm, Figure 15. In the Measurement mode, with the control roller locked parallel to the rollers of the printing press, the variations in the moment and the web tension in the machine direction are recorded. A characteristic result is shown in Figure 16.

During a production run, the press is stopped several times so that the printing plates can be adjusted and changed. The forces of inertia in the press during acceleration and deceleration contribute to the disturbances in the moment and in the web tension. The web tension is also sensitive to the moisture content of the paper. After each stop of the press, the web tension gradually increases as the fountain solution evaporates from the paper. The web tension then drops to the normal value when the press starts again.

The control roller is installed between two printing units in the press. In this position, the strain of the web is constant when the press is running at constant speed. A variation in the tensile modulus of the paper is then registered as a variation in the web tension. After every flying paste, RC in Figure 16 and 18, the web tension increases. This is clearly shown in Figure 17. The higher web tension of the first 2000 m is an effect of the residual stresses in the reel, Rand and Eriksson [10]. This effect has also been measured by Scheuter and Belau [11]. The explanation is that the tangential stress means that the paper is under tension in the outer layers and under compression in the inner layers of the reel, which influences the dynamic tensile modulus of the running web.

In Figure 17, the bending moment M also varies as a function of the running length of the web. This variation is different in the different reels because the mechanical properties of the paper vary across the web.

In the Automatic control mode, the stepping motor adjusts the control roller to a position where the bending moment M is zero. The displacement of the shaft end of the control roller, u, is used to characterize the tensions in the web. Figure 18 shows a recording over a period when the printing press was running at a constant speed. The variations recorded were thus mainly due to changes in the properties of the web. The web tension, S, was constant with the exception of the first two minutes after a reel change. During this period, the web tension had a higher value because of the residual stresses in the reel. Figure 18 shows that the variation in the moment, characterized by u, increases gradually after a reel change. The explanation of this phenomenon is not clear. This means that the stability of the web varies with the reel diameter.

The greatest disturbances in the bending moment occur, however, during the reel changes. The runnability of the web depends to a large extent on how successful the control system is in suppressing these disturbances. The capacity of the control roller system to compensate for the disturbances associated with an automatic reel change is demonstrated in Figure 19. Without any compensation, the moment M_a in Figure 19 changes by about 25 Nm when the reel is changed. Three factors contribute to the variation in the moment. The first factor is the disturbance of the flying splice itself. This disturbance lasts for a few seconds until the splice has passed the printing units. The second factor is the mechanical properties of the paper. The change in bending moment remains after the reels have been changed, as is shown by curve M_a in Figure 19, which indicates that the reels before and tafter the change have different mechanical properties across the web. The third factor is the web tension in the machine direction. To what extent this influences the bending moment is a matter both of the alignment of the rollers and of variations in the mechanical properties of the paper across the web.

The moment has a short rise time when a new reel is introduced because of the sudden change in mechanical properties. At normal press speeds the rise time of the moment is of the same order as the response time for a change in the roller angle. The control system changes the angle of the control roller by 0.03 degrees per second within ± 0.0015 degrees. In practice this means that the moment in the Automatic control mode is controlled within ± 2 Nm and that the disturbances when a new reel is introduced are eliminated. This is shown by the curve M_b in Figure 19. If the lengths of the web spans are changed, the rise time of the moment and the response time of the control roller are changed in the same proportion [8]. The general conclusion is that the moment can be controlled at any position on the press during an automatic reel change at full press speed.

It is always difficult to trace the origin of runnability problems in a newspaper printing press. The web tension S and the displacement of the control roller u characterize the stability of the web. To find out whether recorded data relating to the behaviour of the control system contain useful information, a dedicated test has been performed with 30 newsprint reels. All the reels were produced at the same time in one paper machine. Half of the reels were printed within three days. The other half of the reels were stored for three months before being printed. Figure 20 shows recorded data for two reels with different web-stability curves. The reel c has a moment which varies almost linearily as a function of the length of the running web. This means that the resultant force of the web tension slowly turns to become more parallel to the machine direction. The reel d exhibits variations in the moment but a constant mean. The wavelength of the variation in the moment is of the order of one thousand metres.

A comparison of data for the reels printed directly and for the reels printed after storage showed that the reels from the same position of the paper machine had very similar web-tension and moment curves. This is illustrated in Figure 21. The two reels have almost identical u-curves. The conclusion is that the characteristic variation in the moment and in the web tension is an inherent property of the paper preserved during storage. The control-roller system is consequently a feasible tool to record and to characterize the behaviour of the reel.

In a printing press, the stresses at the edges of the webs are crucial for the runnability. The installation of a control-roller system on a web which eliminates the bending moment in the web due to variations in the web tension across the web gave substantial improvements in a newspaper printing press. Several hundred reels have been printed without web breaks. The web-break frequency in the printing press was usually aboutt 4 breaks per 100 printed reels.

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Table 1. Results of a theoretical calculation on the experimental set up for a full width printing press outlined in Figure 14. The moment, the shear force and the lateral displacement of the web span upstream, BC, and downstream, CD, of the control roller are calculated.

Values of the parameters of the web:

u = 1 mm	Θ = 0.03°	BC = 0.68 m
S = 100 N/m	Eh = 300 kN/m	C D = 1.42 m
φ = 27°	ψ = 9°	W = 1.64 m

G	g	BC $K_sL = 2.6 \cdot 10^{-2}$			C D $K_sL = 5.5 \cdot 10^{-2}$			$Y_C - Y_D$
N/m^2		M_B Nm	N_C N	Y_C mm	M_C Nm	N_C N	Y_D mm	mm
I 0.4 E	0	152	223	0.21	81	57	0.25	- 0.04
I 0.4 E	$1 \cdot 10^{-3}$	38	56	0.29	48	34	0.15	0.15
III 0.2 E	$2 \cdot 10^{-3}$	21	32	0.31	34	24	0.10	0.20

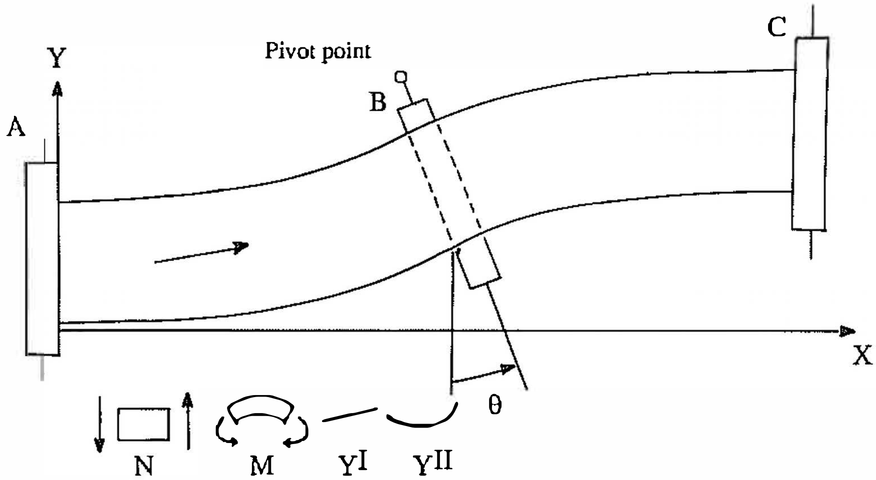


Figure 1. Symbols used in the beam model of the web. A and C are fixed rollers and B is an adjustable roller. The figure shows the positive directions of the shearing force N, the bending moment M, the slope of the Web Y^{I} and the curvature of the Web Y^{II}.

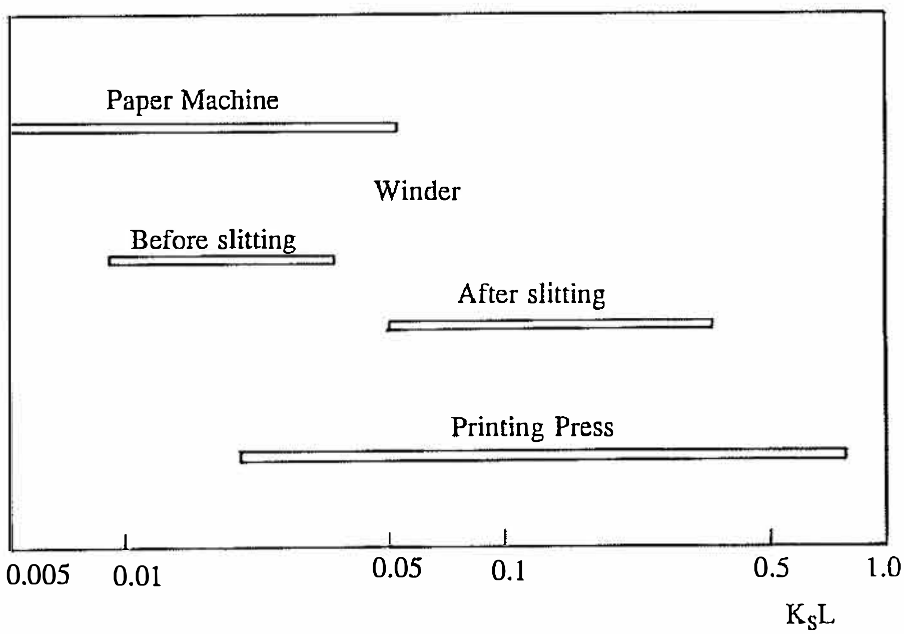
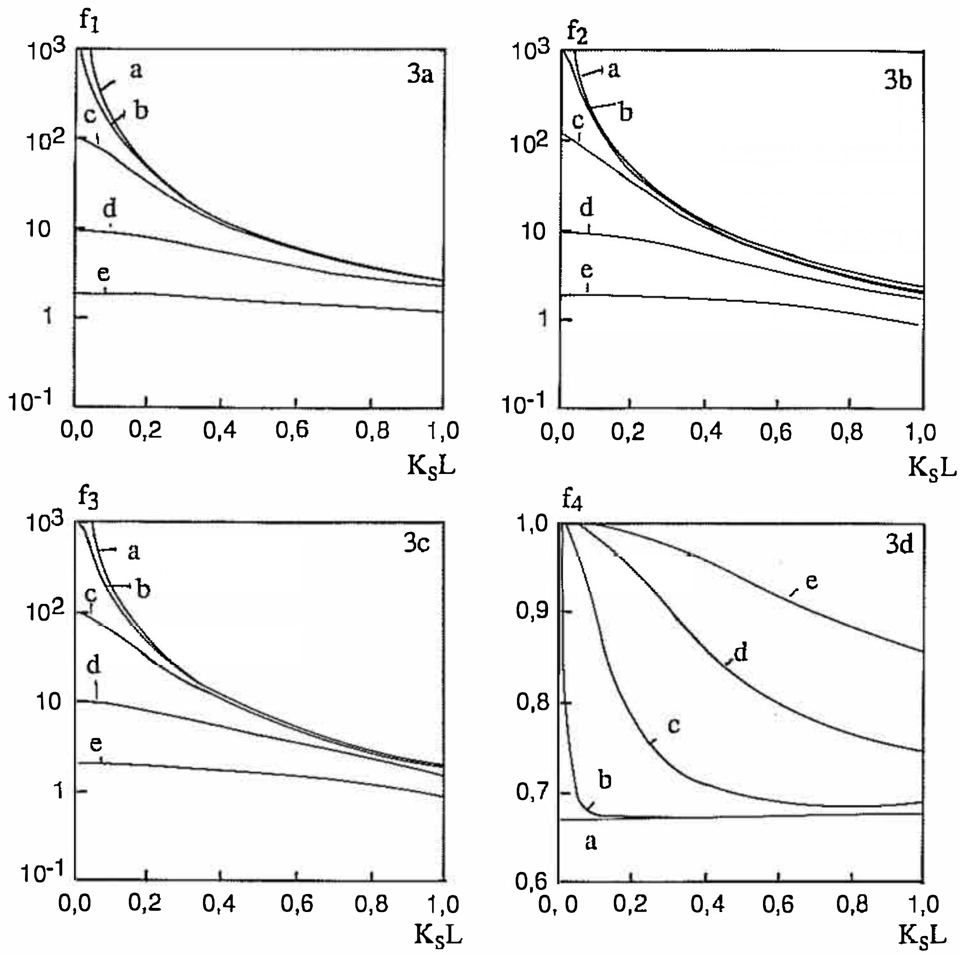


Figure 2. The range of the parameter K_sL in newsprint webs.



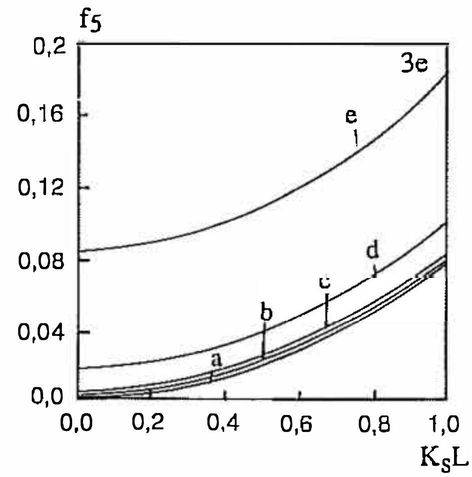


Figure 3a-3e.- Influence of the parameters K_SL and g on the functions f_1-f_5 calculated for the span AB in Figure 1. Figures 3 a and 3 b reflect the shear force and moment at roller A. Figures 3 c and 3 d reflect the shear force and the lateral displacement at roller B and Figure 3 e reflects the critical angle.

Curve	g-value
a	0
b	0.001
c	0.01
d	0.1
e	0.5

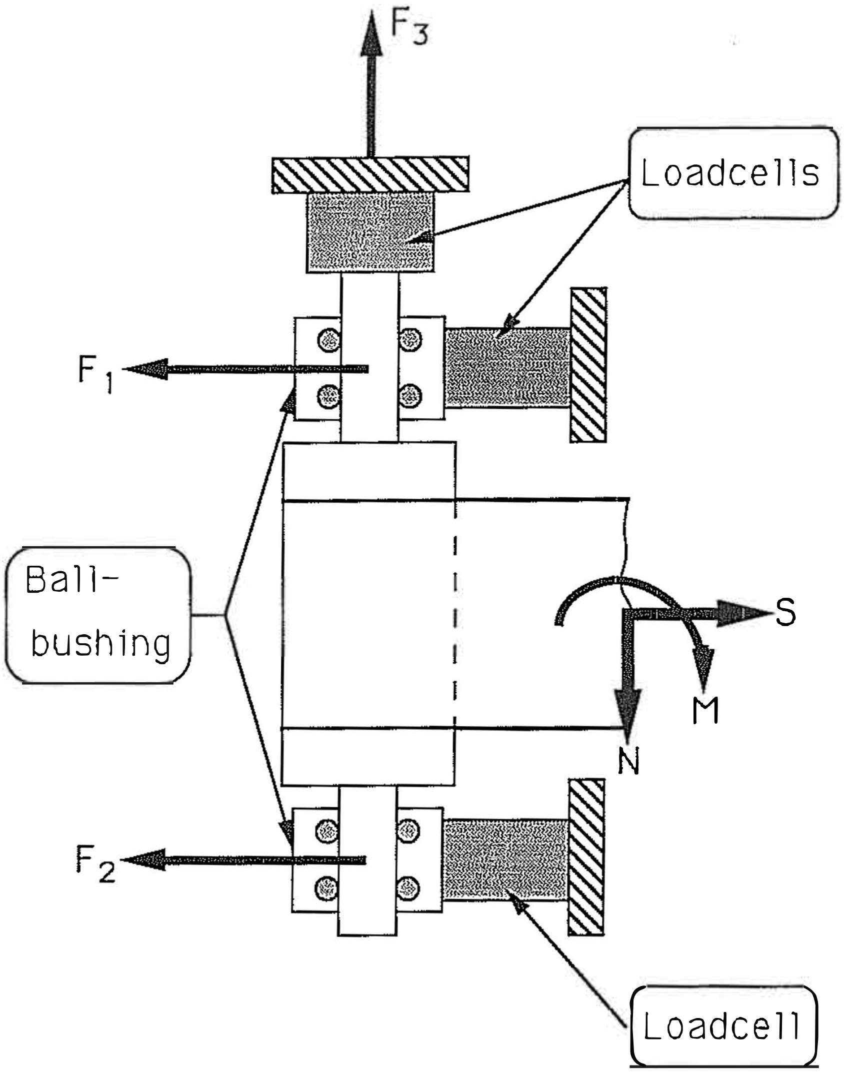


Figure 4. Principle of measurements.
The forces F_1, F_2 and F_3 are measured by load cells. The shear force is proportional to F_3. The web tension in the machine direction is proportional to F_1+F_2 and the moment proportional is to F_1-F_2.

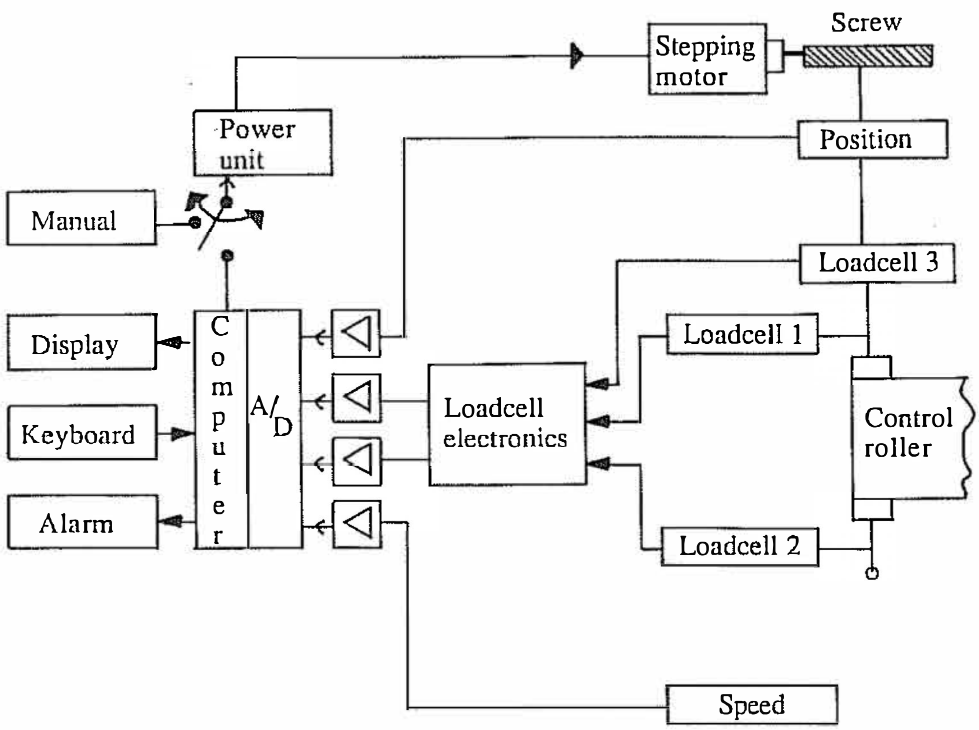


Figure 5. Component parts of the microprocessor control system for the control roller.

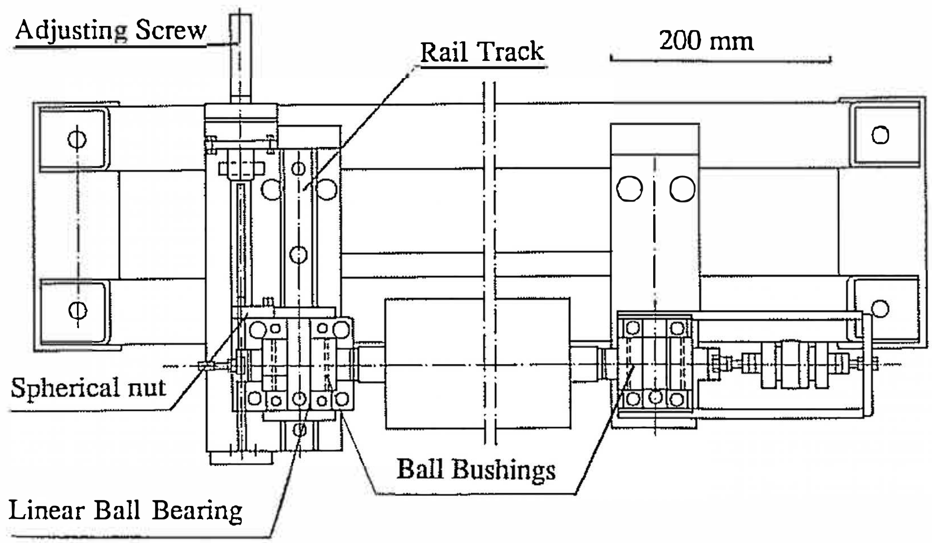


Figure 6. Mechanical design of the control roller.

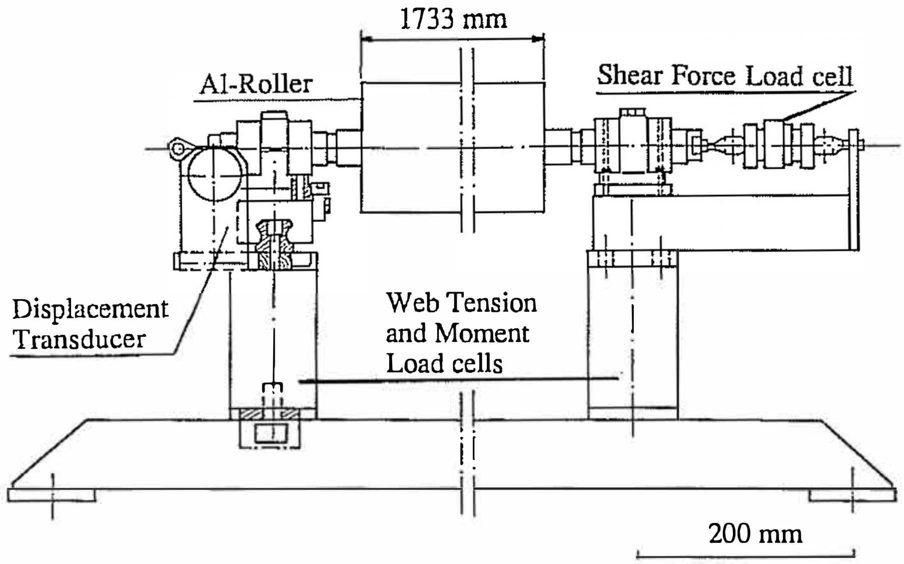


Figure 7. Measuring transducers of the control roller.

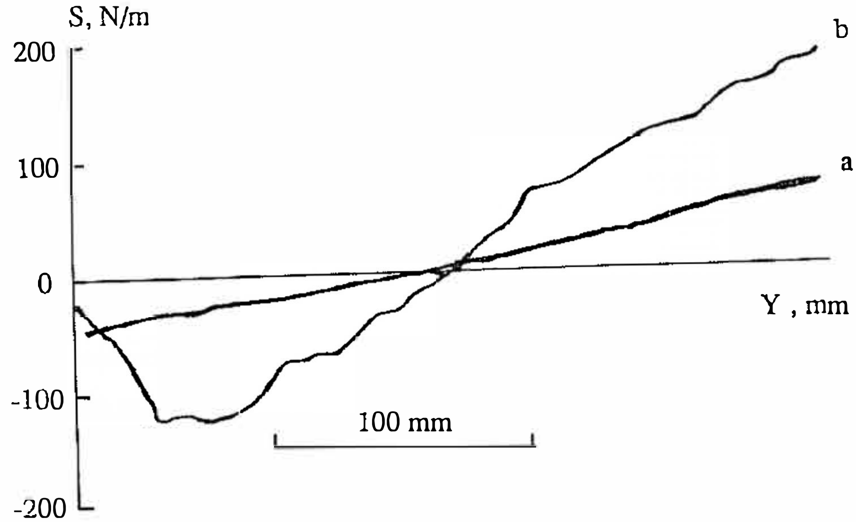


Figure 8. Characteristic changes in the web-tension profile.
Curve a is the change in the profile if $\Theta < \Theta_{cr}$ and
Curve b is the change in the profile if $\Theta > \Theta_{cr}$

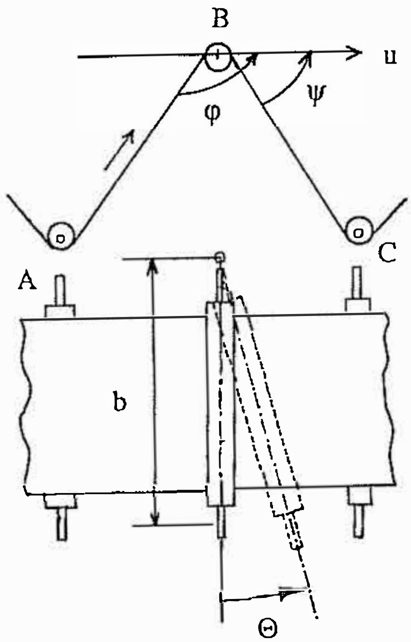


Figure 9. Symbols used to describe the position of the control roller in the web lead.

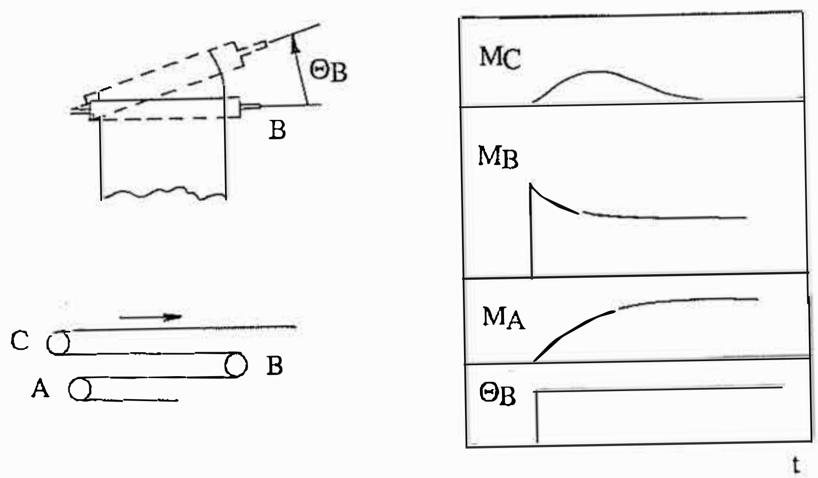


Figure 10. Moment responses to a step change of the angle of the control roller.

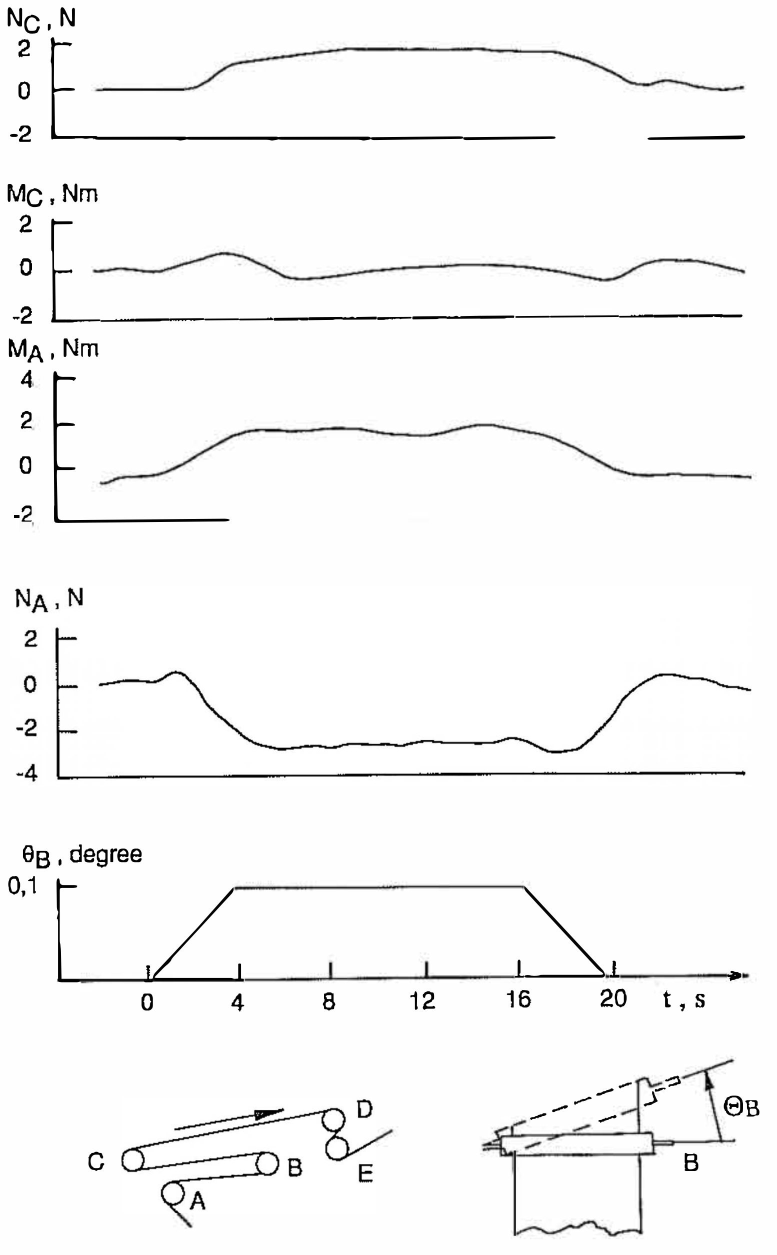


Figure 11. Recorded responses at the downstream and upstream rollers following a change in the angle of the control roller in a laboratory test.
Parameters of the web:

W = 300 mm	V = 1 m/s	S = 150 N/m
AB = 1.0 m	BC = 1.5 m	CD = 2.0 m

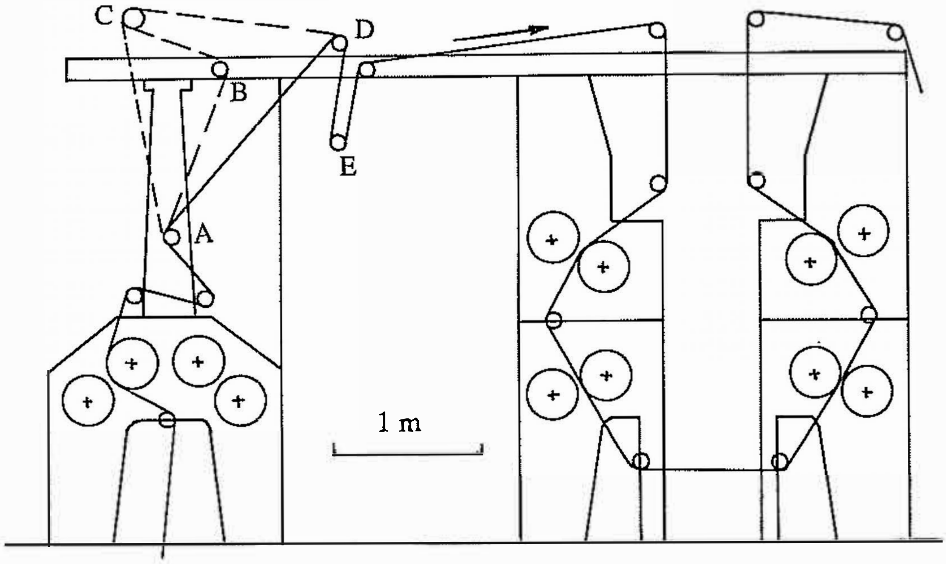


Figure 12. Web leads in the printing press. The standard web lead is ADE. The web lead ABCDE is used for the control system. C is the control roller. B is the extra roller installed.

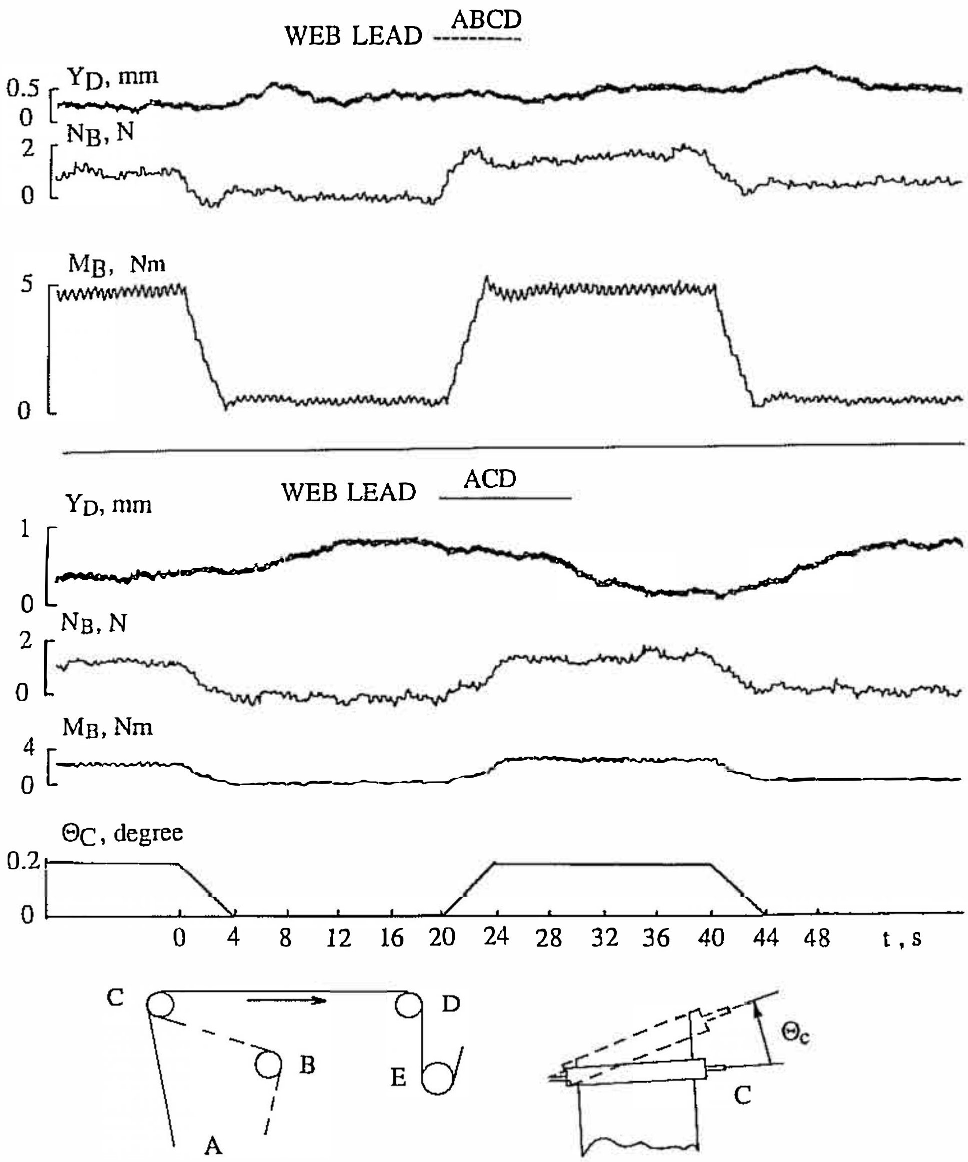


Figure 13. Laboratory tests with the same web leads as in the printing press.
Parameters of the web:

W = 300 mm	V = 1 m/s	S = 300 N/m
BC = 0.68 m	CD = 1.42 m	

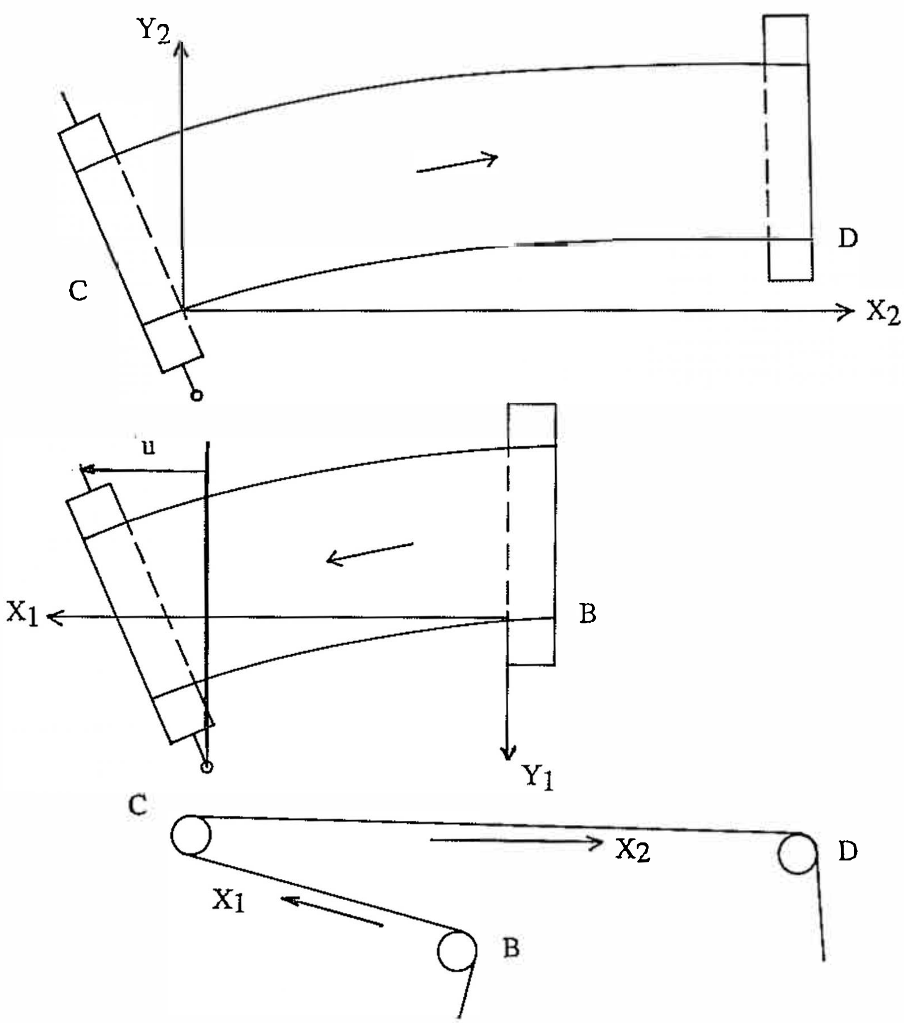


Figure 14. Symbols used to analyse the influence of the control roller on the web in the printing press.

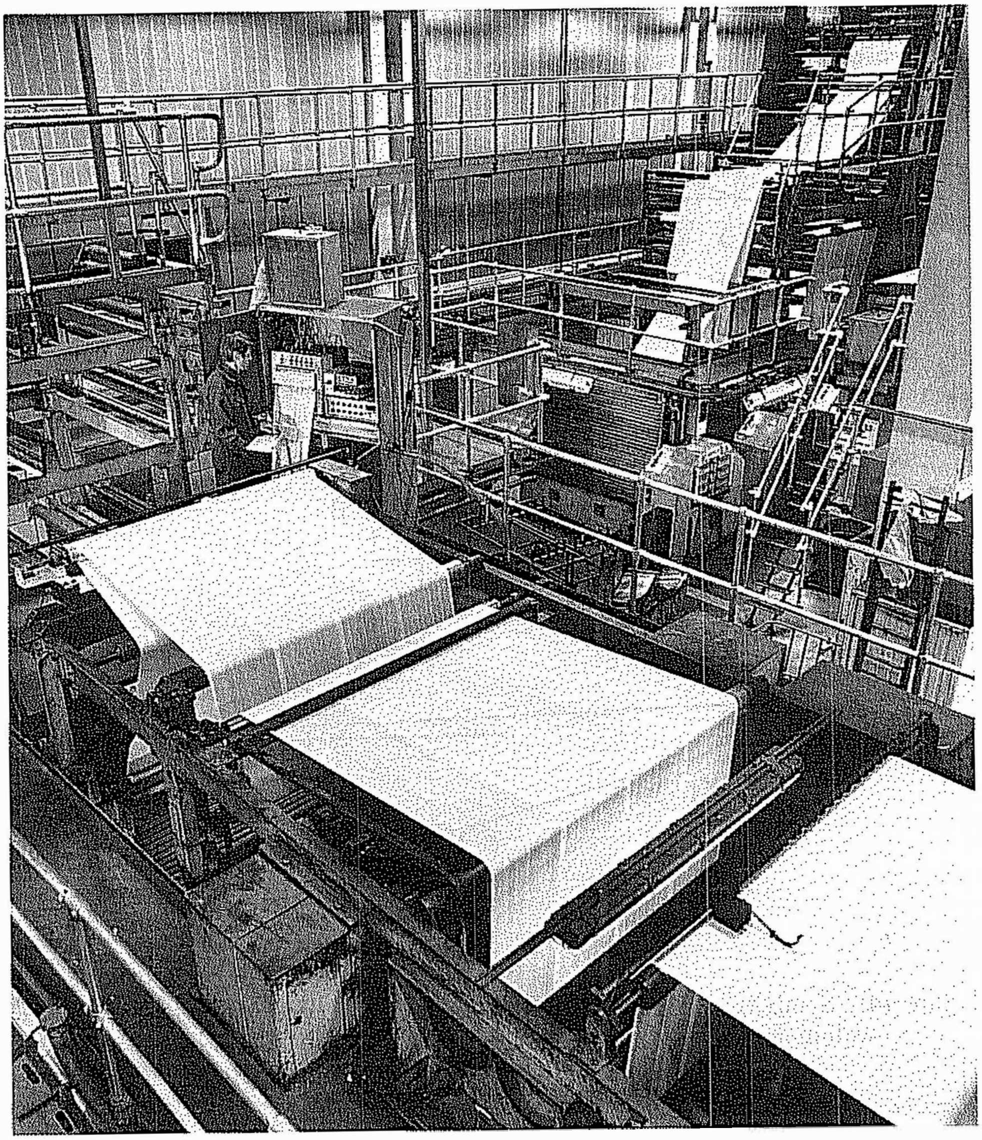


Figure 15. The installation of the equipment in the printing press.

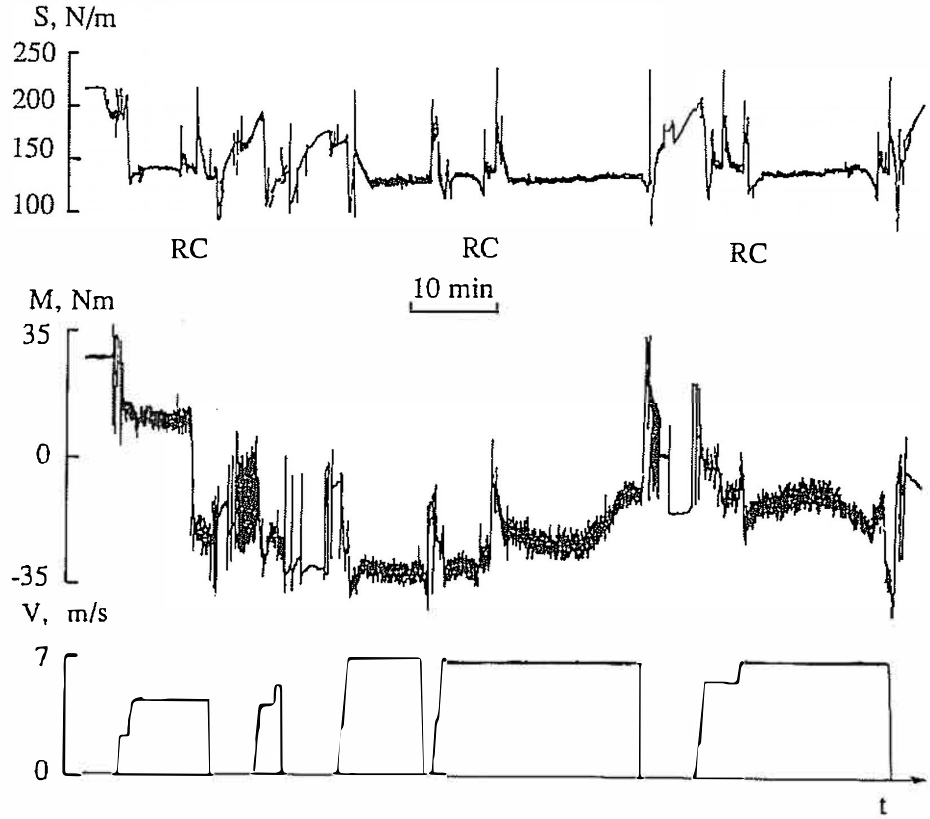


Figure 16. Record of the web tension S and the moment M on the control roller during normal production in the printing press. The control roller is locked parallel to the rollers of the press. The reel changes are marked by RC.

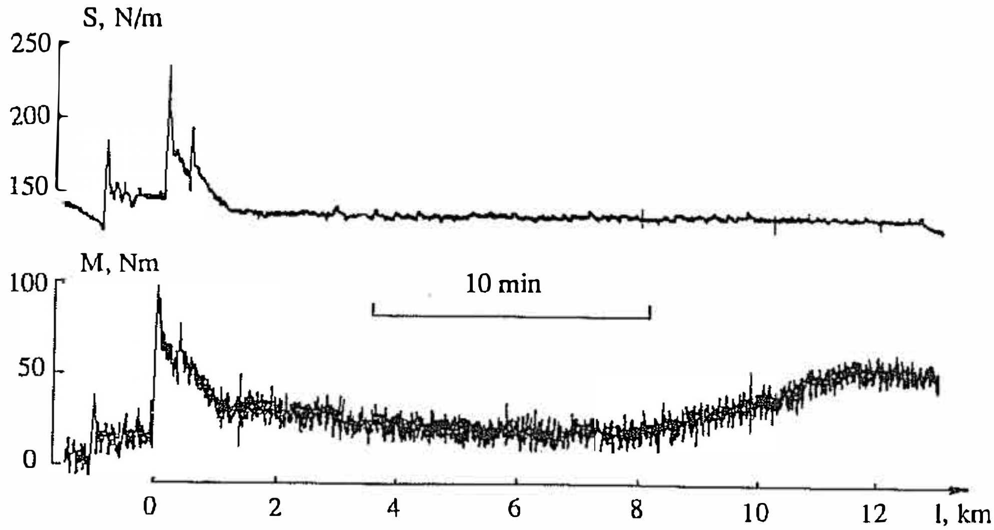


Figure 17. Variations in the web tension S and the moment M within a reel. The control roller is locked parallel to the rollers of the press.

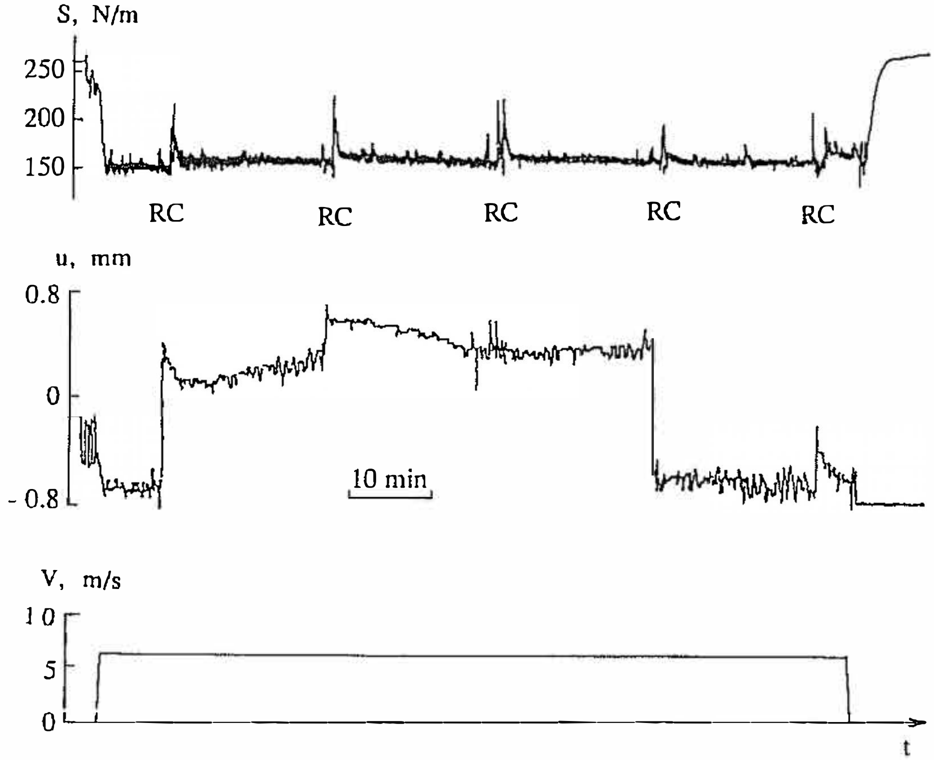


Figure 18. Record of the web tension S and the position u of the control roller during normal production in the printing press. The control roller is controlled by a closed loop. The reel changes are marked by RC.

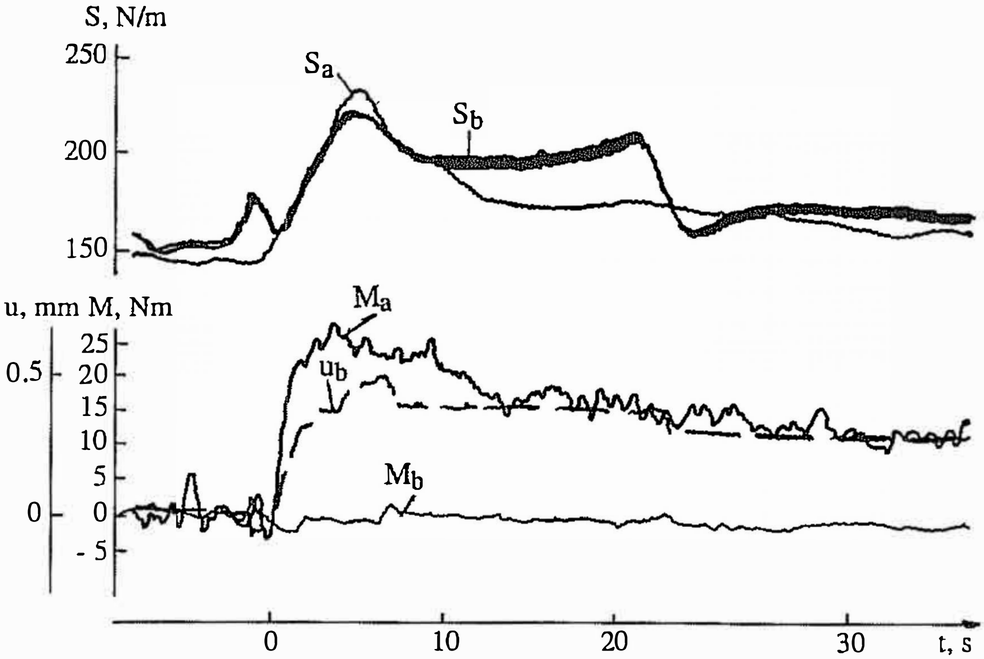


Figure 19. Recorded web tension and moment during two reel changes. Curves with subscript a are without control and curves with subscript b are with closed loop control. S_a and M_a are the web tension and the moment without control. S_b is the web tension, M_b the moment and u_b the position of the control roller with closed loop control. The speed of the printing press was 6.5 m/s.

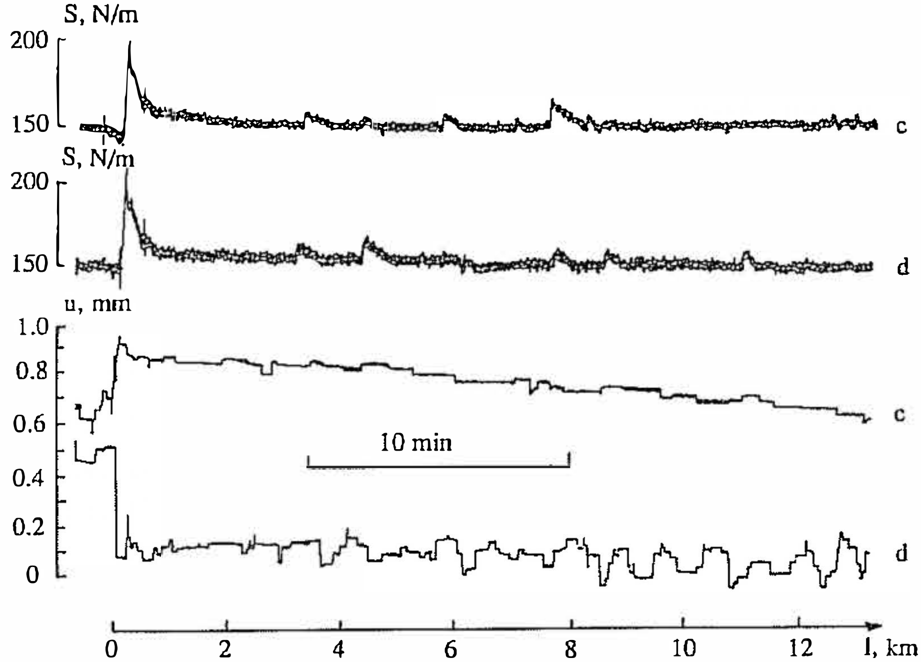


Figure 20. Recorded variations in the position u of the control roller during closed loop control of the moment. The two reels, c and d were taken from different positions in the same machine reel. The press speed was 7.6 m/s.

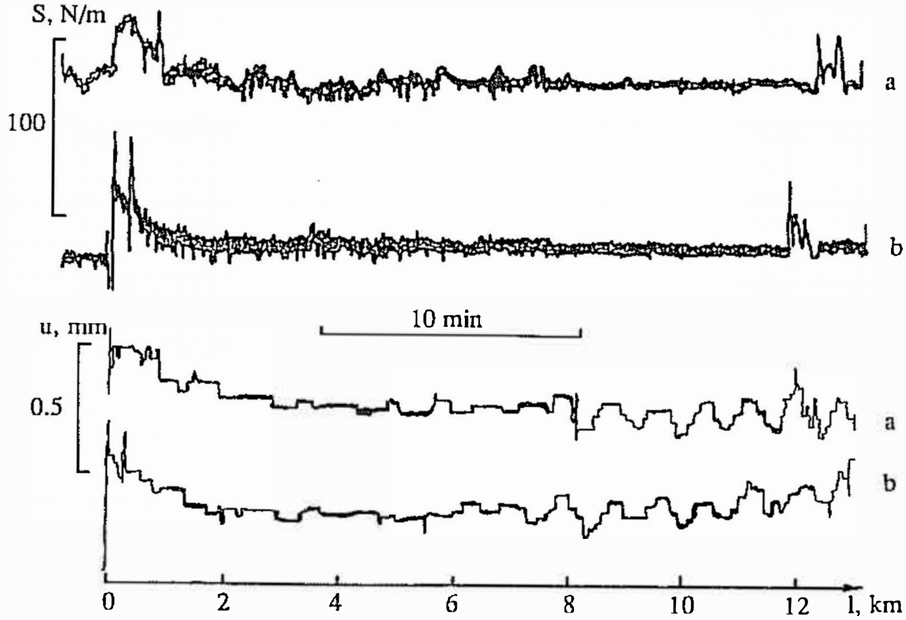


Figure 21. Recorded variations in the position u of the control roller during closed loop control of the moment. The two reels a and b were taken from the same position across the paper machine. Reel b was printed 3 months after reel a. The press speed was 7.6 m/s.