ANALYSIS OF THE KINEMATIC AND DYNAMIC PROCESS DURING WINDING BASED ON A SYSTEMATOLOGY OF MODELS FOR WINDING MECHANICS

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ABSTRACT

The winding process of web materials with low bending resistance is composed of several partial processes whose single effects are influenced by specific machine, process and material parameters. The interaction of these processes causes an essential increase in the difficulty of modeling the total process. Up to now there are numerous mainly experimental investigations concerning the particular effects of the winding process. But they are not sufficient to describe the total process regarding all influences of the machine technology and material properties.

In this regard our institute has developed a systematology of models for winding mechanics which starts with the real winding process of the different winder classifications and resolves the complex total process step by step into partial models. Subsequently it is possible to study the effect of different parameters on the derived partial models based on various degrees of idealisation. By coupling different partial models the modelling of any partial process becomes possible.

The fundamental knowledge of theoretical research work is the mechanic of solid bodies with its analytical methods for highly idealized [simple] models and numerical methods (finite elemente-method (FEM), finite-difference-method (FDM)) for complex, more realistic models.

NOMENCLATURE

a	half width of the nip area
C	constante
E	Youngs modulus of the web in MD
F	force
h	thickness of the web

m mass
p pressure
q friction force per square area
r radius
v velocity
x coordinate
$\bar{x}$ coordinate , dimensionless
α angle
ε strain
φ cylindercoordinate
κ position in the nip
μ coefficient of friction
ν Poisson's ratio
ρ specific mass
σ web stress
$\bar{\sigma}$ web stress incl. the effect of centrifugal forces
ω circumfevential velocity

subscripts:
A exit
E entrance
g position between stick and slip
G slip
H stick
n normal-direction
R friction
U related to the wrapping
1 upper roll ('reel')
2 lower roll

INTRODUCTION

The technical, ecological and economic objectives of the paper industry are changing with a very high dynamic on terms of competition. For this reason the demands on machine technology for paper production and converting as well as on the quality of different pre-products and consumer products intensify especially in context with a sustainable paper cycle. In this regard the importance of the winding technology increases as part of the technological process beginning at the Pope reeler and ending at the trimmed roll [1]. The roots for the increased importance can be found in the demands of quality for the rolls on the one hand (no defects in roll structure, transport stability, no dishing) and on the other hand in the demands on productivity of the converting machines (high and stable machine capacity, increased roll diameter). Furthermore we can realize the change of the paper making process from a classical, discontinuous process with its production and quality losses to a more continuous process with higher demands on the winding technology. On this condition paper producers and machine suppliers are trying to push forward the winding technology. By this an unsufficient fundamental knowledge often becomes obvious. Therefore the objective of this paper is to present and demonstrate a new strategy to study the basic physics of the winding process systematically.

STATE-OF-THE-ART TECHNOLOGY AND RESEARCH

The winding of web materials is mostly done by nip rollers. The nip rollers can be divided in different classes like two drum winders, single drum winders and winders with lay-on-roll. These types of machines have in common that the web is wrapped a roll before it enters the first nip. Depending to the specific machine type even more nips will follow. As experience shows, the nip mechanics are often causing extensive production and quality losses. In a statistical analysis [2] it is pointed out that 87% of the problems occured, originated or were amplified, in the paper mill winding process mostly caused by roll structure and nip induced defects. In this context the essential winding defects are basically [2, 3, 4]: tension, core or air shear burst, wrinkles, buckles, dishing and marks on the surface of the web.

To remove these winding defects the principles of the existing machine designs were at first adapted (e.g. [5]) and then optimized (e.g. [6]), depending on the specific area of application. Based on the knowledge that the winding quality is essentially influenced by the processes in the nip and that excessively nip action has a negative influence on this quality, the machine suppliers developed and introduced machine concepts to reduce the intensity of nip forces. These concepts imply compliant roll covers [7,8], the support of the reels by belts instead of rolls [9] or relieving the nip loads by air pressure [10]. The common aim of all concepts is to reduce and to equalize the paper stresses and nip induced tensions by reduced nip forces and a compliant adjustment of the roll cover to the reel profile.

Since approximately 30 years, the experimental and theoretical research work concerning the nip action was started. Based on the landmark publication of Pfeiffer [11], who studied the nip action on a stack of paper, many investigations concerning the kinetic and kinematic processes in the nip under specific conditions (e.g. [12,13]), the material response to nip forces (e.g. [14,15]) up to numerical solutions based on FE-modells of the nip area (e.g. [16]) followed. All investigations have in common, that the boundary conditions of the entry and exit of the nip could not be taken into account appropriately. Therefore only a limited transfer of the results into the real winding process is possible.

Summing up, we can realize, that the nip action with its parameters of influence is mainly responsible for the quality of the roll sructure and that todays knowledge is inadequate to describe the partial influence of these parameters qualitatively or even quantitatively.

MODELLING OF WINDING PROCESSES BASED ON PARTIAL MODELS

Concerning this background a systematology of models for winding mechanics was developed at our Institute for Engineering Design, which starts with the real winding process of different winder principles and resolves the complex total process step by step into partial models. This procedure is appropriate to analyse the kinetic and kinematic process in the nip by carefully regarding the conditions at the entry and exit of the nip. Fig. 1 clearly shows this basic extend to the modelling of winding processes. As a result the winding process is a repetitive coupling of the basic models

- wrapped roll (or reel for outer layers)
- nip with included web

independent of the specific class of winder. The strategy of modelling can be described as follows: At first there are partial modells with different degrees of idealisation concerning geometry, kinematics, kinetics and material properties studied by means of analytical or numerical methods. After that the partial models with their specific degree of idealisation are coupled and carefully attention is paid to the boundary conditions at the interfaces. With this coupling the analytical and numerical solving concepts of the partial models are joined together and allow thereby the solving of the coupled problem.

Table 1 + 2 show a part of the systematology of models for winding mechanics. In Table 1 we can see different partial models in every line like 'wrapped roll'(1A), 'nip'(2A-2C) or 'nip with included web'(3A-3C) up to an example for a coupled model 'wrapped roll coupled with nip'(4A-4C). The different column A to C show variations in the kinetic boundary conditions.

Table 2 gives an example of a reel in different degrees of idealisations (line 1 to 5) respectively each of these degrees with different kinetic boundary conditions (column A to C). Instancing the different degrees of idealisation for the Archimedean spirale of a reel we arrive at the following models: The extreme form of idealisation is to regard the reel as a solid body with infinite radius (1A) or finite radius (2A). Although it is the easiest model of a reel we can already study the influence of the nip load and torque on the distribution of stress and deformations. Comparatively closer to reality is already a partial modell (3A), in which the reel is sustituted by a stack of paper as it was used in [11] for experimental investigations. In this case it is possible to analyse the parameter of influence on layer to layer slippage. To observe furthermore the influence of reel radius it is suitable to use a ring approximation for each layer. This is the common model for calculating the roll hardness as a function of roll radius. However, the complete interactions between the layers in a reel can only be simulated by an Archimedean spirale, as it is shown in model 5A. Similar steps of idealisation are stated for the roll which is in contact with the reel.

Furthermore it is possible to define for every partial model different assumptions concerning the material law for web and roll cover, the friction behaviour of the material combinations and the dimension of the considerations (2 or 3-dimensional).

Finally the variations of the kinematic and kinetic boundary conditions lead to a complete systematology. In this context the item 'kinematic conditions' implies all assumptions concerning wrap angle, web guidance, position and number of rolls as well as web strain, whereby the item 'kinetic conditions' describes the assumptions concerning induced forces and torque as well as web tension.

By this means we obtain partial models which are the foundation for a systematic extension of the basic knowledge. Based on the mechanic of solid bodies there will be derived the analytical solution of the

- kinematic process: resulting in a strain state
- kinetic process: resulting in a stress state

starting with models with a high degree of idealisation. By these solutions the influence of different parameters can be quantified. The solutions also serve as a base for solving more and more complex models with sucessively decreasing degree of idealisation. If it is not possible to find an analytical solution anymore, numerical methods (FEM, FDV) will be used. Furthermore it can be succeeded in solving any winding process by coupling the partial models.

Below we will demonstrate the presented method instancing the basic models 'wrapped roll', 'nip with web included' and the coupling of both 'wrapped roll coupled with nip' (see Table 1: models 1A, 3A and 4A).

Partial Model „Wrapped Roll"

In case of the wrapped roll the development of strain and stress as a function of wrap angle are well known in form of the Capstan Formula (2). However, we want to reflect and to comment on the assumptions and idealisations needed to solve the underlied differential equation.

Assuming that

- Gravitational forces are neglectible.
- The web material has low bending resistance.
- steady-state condition
- Amontons' law is valid.

the differential equation for the basic model 'wrapped roll'(resp. reel, see Fig. 1+2) can be derivated to:

$$d\bar{\sigma} \cdot A - \mu \cdot (\bar{\sigma} \cdot A \cdot d\varphi - dm \cdot r \cdot \omega^2) = dm \cdot \ddot{\varphi} \tag{1}$$

Defining the web stress $\sigma = \bar{\sigma} - v_E^2 \cdot \rho$ leads to the well known Capstan Formula, here shown in case of a driven roll:

$$\frac{\sigma_A}{\sigma_E} = e^{\mu \cdot \alpha_G} \quad \text{resp.} \quad \sigma(\varphi) = \begin{cases} \sigma_E & \text{for} \quad \varphi < \alpha_H \\ \sigma_E \cdot e^{\mu \cdot (\varphi - \alpha_H)} & \text{for} \quad \varphi \geq \alpha_H \end{cases} \tag{2}$$

By including a suitable material law (e.g. Hookes law) and neglecting the cross contraction, the strain as a function of the wrap angle φ can be concluded:

$$\varepsilon(\varphi) = \begin{cases} \varepsilon_E & \text{for} \quad \varphi < \alpha_H \\ \varepsilon_E \cdot e^{\mu \cdot (\varphi - \alpha_H)} & \text{for} \quad \varphi \geq \alpha_H \end{cases} \tag{3}$$

If we substitute the web strain by web velocity on the basis of a constant mass flow, we get:

$$v(\varphi) = \begin{cases} v_E & \text{for} \quad \varphi < \alpha_H \\ v_E \cdot \dfrac{1 + \varepsilon_E \cdot e^{\mu \cdot (\varphi - \alpha_H)}}{1 + \varepsilon_E} & \text{for} \quad \varphi \geq \alpha_H \end{cases} \tag{4}$$

Comparing the velocities between web and roll and an energetic consideration, we can explain the location of the stick and slip areas. An energy transfer is only possible from the faster to the slower partner. Therefore, in case of a driven roll, the web has to move faster as the roll. In the stick area web and roll have the same velocity. Because the velocity can change only gradually, the stick area has to be in the entry of the roll followed by a slip area where the web speeds increases as shown in Fig. 3. In case of a driving roll, an analogous consideration leads to the same result.

The Capstan Formula seems to be suitable for the description of the kinematic and kinetic behaviour for instant of a web wrapping a roll or the outer layer of a reel (see Fig.1). However, its validity is limited due to the assumption as shown in the following.

The derivation is based on a linear friction law which is often referred as Amomtons' law ($dF_R = \mu \cdot dF_n$). It postulates that the friction force in case of slip depends only on the friction coefficient and the normal force. A particulary consideration discloses that there has to be regarded high-order effects [15]. It is well known, that the friction behaviour is influenced by adhesive effects of the surfaces and chemical substances leaving the web (especially in case of coated papers). Therefore it is not possible to describe the behaviour in reality in a completely manner by using only Amontons' law.

Furthermore it is supposed that the friction coefficients of stick and slip have the same value. In reality the friction coefficient for sticking is higher than for slipping [17]. This can cause stick-slip effects on the wrapped roll.

By derivating the Capstan Formula a uniform strain and stress distribution along the roll axis is assumed. At the web edges this assumption is not accurate. FEM calculations have pointed out an extend of the slip angle at the web edges [18].

Partial model 'nip with web included'

A nip is considered as the contact area of two cylindrical bodies in rolling contact. In a winding process there are one or more nips between the reel and rolls depending of the type of winder. By modelling the reel in a first step as a solid body with finite radius (see Table 1 and also Table 2, model 2A) we can describe some fundamental considerations as follows:

In the case of torque transmission we can observe a sliding between roll and reel. That means that the circumferential velocities of the two undeformed bodies are different. This occurs in case of completely different circumferential velocities where there is sliding in the whole contact area as well as in the case of an existing stick area between roll and reel. Whereby the former case is only interesting for theoretically investigations because roll and reel are executing an uncoupled movement, the latter case is usually found in the real process. Sliding in this case is caused by the influence of elastic deformations on rolling contact. The whole contact region can be divided into stick and micro-slip zones in a manner determined by the interplay of the friction forces and elastic deformations.

The strain level of the roll and reel in the stick area then determines the amount of sliding.

There exists a well known system of equations (see e.g. [19]) that describes the kinetic and kinematic conditions in the nip. But it can only be solved analytically for a few applications with special asssumptions.

In [20] are presented results for the extended model of the 'nip with included web' as shown in Fig. 4. By assuming a web with low bending resistance and a web thickness essentially less than the nip area, the function of stress can be described as:

$$\sigma(x) = \sigma_E + \frac{1}{h} \cdot \int_{-a}^{x} [q_1(u) - q_2(u)] \cdot du \qquad (5)$$

Assuming plane strain condition leads to:

$$\varepsilon(x) = \varepsilon_E + \left[\frac{1-\nu^2}{E \cdot h} \cdot \int_{-a}^{x} [q_1(u) - q_2(u)] \cdot du + \nu \cdot (1+\nu) \cdot \frac{p(x)}{E}\right] \tag{6}$$

These equations characterize the behaviour of the basic model 3A in Table 1. Hereby we focus on the contact area between web and rigid roll 2.

In the stick area two conditions have to be fulfilled:

1. The strain gradient has to be zero:

$$\frac{d\varepsilon}{dx} = \left[\frac{1-\nu^2}{E \cdot h} \cdot (q_1(x) - q_2(x)) + \frac{\nu \cdot (1+\nu)}{E} \cdot \frac{dp}{dx}\right] = 0 \tag{7}$$

2. The friction forces shall not exceed the limiting value by Amontons' law:

$$|q_2(x)| \le \mu_2 \cdot p(x) \tag{8}$$

If eqs. (7) and (8) are fulfilled, it is not consequently necessary that there will exist a stick zone. The existance of a stick zone depends furthermore on the boundary conditions as will be demonstrated in detail later.

The friction forces in the slip area are calculated to:

$$q_2(x) = -\mathrm{sign}(v - v_2) \cdot \mu_2 \cdot p(x) \tag{9}$$

The location of the stick and slip zones in the contact area can not be determined in general, because this would assume that we know the pressure distribution p(x) in conjunction with the friction distribution $q_1(x)$.

If we suppose an elliptical (Hertzian) pressure distribution and a frictionless contact between web and roll 1 ('reel'), we receive a system of equations which can be solved analytically. This case would correspond to a partial model 'nip with included web' on a high degree of idealisation.

By introducing a dimensionless coordinate system ($\bar{x} = x/a$) we can describe the pressure distribution as:

$$p(\bar{x}) = p_0\sqrt{1-\bar{x}^2} \tag{10}$$

Combining eqs. (6) and (7) with eq. (10) gives:

$$\varepsilon(\bar{x}) = \varepsilon_c + \left[-\frac{1-\nu^2}{E} \cdot \frac{a}{h} \cdot \int_{-1}^{\bar{x}} q_2(\bar{u})d\bar{u} + \nu \cdot (1+\nu) \cdot \frac{p_0}{E} \cdot \sqrt{1-\bar{x}^2}\right] \tag{11}$$

$$\frac{d\varepsilon(\bar{x})}{d\bar{x}} = \left[\frac{1-\nu^2}{E} \cdot \frac{a}{h} \cdot q_2(\bar{x}) - \nu \cdot (1+\nu) \cdot \frac{p_0}{E} \cdot \frac{\bar{x}}{\sqrt{1-\bar{x}^2}}\right] \tag{12}$$

Again sticking between web and roll 2 is only possible if the strain gradient is zero and the inequation (8) is fulfilled. These conditions and the introduction of the constant $C = \frac{\nu \cdot h}{(1-\nu) \cdot \mu_2 \cdot a}$ leads to the location of the possible stick zone, which can be described as follows:

$$-\kappa \le \bar{x} \le \kappa \qquad \text{with} \qquad \kappa = -\frac{C}{2} + \sqrt{\left(\frac{C}{2}\right)^2 + 1} \tag{13}$$

whereby $|\kappa| \le 1$. In the area $-1 \le \bar{x} < -\kappa$ and $\kappa \le \bar{x} < 1$, that means at the entrance and the exit of the nip always exists a slip zone, because the conditions for sticking cannot be fulfilled. In case of a neglectible Poisson's ratio follows $|\kappa| = 1$, so that the possible stick zone contains the complete nip area. The friction forces in the stick zone are determined by setting eq. (12) to zero:

$$q_2(\bar{x}) = \frac{\nu \cdot h}{(1-\nu) \cdot a} \cdot p_0 \cdot \frac{\bar{x}}{\sqrt{1-\bar{x}^2}} \tag{14}$$

Eq. (14) shows, that the friction forces in the stick zone are only caused by the Poisson's ratio. The web tends to stretch under normal pressure. In the stick zone the friction forces prevent the stretching of the web. Only at the edges of the nip the stresses causes by Poisson's ratio are extending the friction forces so that the web starts to slip.

The friction force in the slip zone can be expressed by combining eqs. (9) and (10) to:

$$q_2(\bar{x}) = -\text{sign}(\nu - \nu_2) \cdot \mu_2 \cdot p_0 \cdot \sqrt{1-\bar{x}^2} \tag{15}$$

Substituting eq. (15) into (12) yields to:

$$\frac{d\varepsilon(\bar{x})}{d\bar{x}} = \frac{p_0}{E} \cdot \nu \cdot (1+\nu) \cdot \left[\frac{1}{C} \cdot \text{sign}(\nu - \nu_2) \cdot \sqrt{1-\bar{x}^2} - \frac{\bar{x}}{\sqrt{1-\bar{x}^2}}\right] \tag{16}$$

Because strain- and velocity gradient only differ with a constant, the following explanation concerning the existence and location of slip and stick zones will be based on the more illustrative velocity gradient.

Table 3 shows the sign of the velocity gradient as a function of the partial nip zone in case of a web velocity less ($v < v_2$, line 1) respectively greater ($v > v_2$, line 2) than the circumferential velocity of the roll 2. By means of considering the different conditions of the two cases it succeeds to localize the stick and slip zones for different boundary conditions at the exit of the nip, as shown in Fig. 5.

Considering the case $v_E > v_2$, the velocity gradient is greater zero for the area $-1 \le \bar{x} < \kappa$ .Consequently it cannot exist a stick zone, because the difference of the web and roll velocity is even increased by the positive velocity gradient. Considering, however, the case $v_E < v_2$, the velocity gradient is still positive, but now it reduces the difference of the velocities of the web and the roll. If $v < v_2$ at position $\bar{x} = -\kappa$ a stick zone is again impossible, because the velocity gradient changes its sign at this position and starts to increase the velocity difference for the rest of the nip. Only if $v = v_2$ for $\bar{x} = -\kappa$ a stick zone is possible. the extension of the stick zone depends on the boundary condition at the end of the nip as shown in Fig. 5.

Coupling of the Partial Models

Partial models as they are analysed in this paper can be found in many parts of the paper making process (see Fig. 6). Although their individual character is quite different, they all can be idealized by coupling a few basic models. After recieving the analytically solutions for these partial models it is now possible to transfer the solutions to coupled models which are more suitable for the representation of the reality.

This will be demonstrated instancing the 'wrapped roll coupled with a nip' (see Table 1: model 4A) as it is shown in Fig. 7. The upper roll ('reel') will be represented again only by an elliptical pressure distribution, that means there is no friction between web and the upper roll. The location of the nip (described by φ_0) can be chosen without any restriction. For the following considerations we chose the end of the wrap angle. The pressure distribution is described by using a local, dimensionless coordinate system
$\bar{x} = (\varphi - \varphi_0) \cdot r_2/a$ as:

$$p(\bar{x}) = \begin{cases} p_0\sqrt{1-\bar{x}^2} & \text{für} \quad |\bar{x}| \le 1 \\ 0 & \text{für} \quad |\bar{x}| > 1 \end{cases} \tag{17}$$

The pressure distribution $p_U(\varphi)$, caused by the web tension is:

$$p_U(\varphi) = \sigma(\varphi) \cdot \frac{h}{r_2} \tag{18}$$

Considering at first the nip area ($|\bar{x}| \le 1$) eqs. (11) and (12) are still valid if we neglect the influence of Poisson's ratio due to the pressure distribution $p_U(\varphi)$.

As already well known stick zones necessarily require a zero strain gradient and friction forces given by:

$$|q_2(\bar{x})| \le \mu_2 \cdot [p(\bar{x}) + p_U(\bar{x})] \tag{19}$$

Substituting the first condition and eqs. (17) and (18) into eq. (19) yields to:

$$\left|-\frac{v \cdot h}{(1-v) \cdot a} \cdot p_0 \cdot \frac{\bar{x}}{\sqrt{1-\bar{x}^2}}\right| < \mu_2 \cdot \left[p_0 \cdot \sqrt{1-\bar{x}^2} + \sigma(\bar{x}) \cdot \frac{h}{r_2}\right] \tag{20}$$

The friction force on the slip area is:

$$q_2(\bar{x}) = -\mathrm{sign}(v-v_2) \cdot \mu_2 \cdot \left[p_0 \cdot \sqrt{1-\bar{x}^2} + \sigma(\bar{x}) \cdot \frac{h}{r_2}\right] \tag{21}$$

Again the strain gradient can be derived by substituting eq. (21) into eq. (12):

$$\frac{d\varepsilon(\bar{x})}{d\bar{x}} = \frac{p_0}{E} \cdot v \cdot (1+v) \cdot \left[\frac{1}{C} \cdot \mathrm{sign}(v-v_2) \cdot \left(\sqrt{1-\bar{x}^2} + \frac{\sigma(\bar{x})}{p_0} \cdot \frac{h}{r_2}\right) - \frac{\bar{x}}{\sqrt{1-\bar{x}^2}}\right] \tag{22}$$

The stress function $\sigma(\bar{x})$ in eqs. (20) and (22) can be replaced in condition of plane strain by:

$$\sigma(\bar{x}) = \frac{E}{1-v^2} \cdot \varepsilon(\bar{x}) - \frac{v}{1-v} \cdot p_0 \cdot \sqrt{1-\bar{x}^2} \tag{23}$$

Outside the nip area the Capstan Formula is valid. The strain gradient is given by:

$$\frac{d\varepsilon(\varphi)}{d\varphi} = \begin{cases} 0 & \text{for stick zone} \\ \mathrm{sign}(v-v_2) \cdot \mu_2 \cdot \varepsilon(\varphi) & \text{for slip zone} \end{cases} \tag{24}$$

Based on this system of equations it is possible to calculate the strain as a function of wrap angle by using the Finite Difference method. A first verification of the used algorithem was obtained by comparing the calculated results for the case: nip pressure equals zero with the analytical solution based on the Capstan Formula.

The numerical calculation of the strain is carried out backwards from the exit of the nip step by step to the entry on the roll. At every step the direction of the friction force is determined by comparing the actuall strain with the strain in the stick area or determing the sign of the pressure gradient. Furthermore it is checked if the condition for sticking or slipping still is valid. Afterwards the new strain is calculated, based on the equation which is in this case valid.

In the following we present the results of two examples, whose calculation parameters are listet in Table 3. At example 1 we will study the generell location of the stick and slip zones. Here we chose a nip pressure as it is used in calandering of paper to show the kinematic effects more clearly. The parameter of the second example are typical for winding conditions. In both cases the Poisson's ratio of the web was 0.3.

For example 1 we have calculated strain function for different boundary condition as shown in Fig.8. Curve C (strain at the entrance and the exit is identical) shows two slip areas: at the end of the wrap angle up to the entrance of the nip area and at the end of the nip area. At the entrance of the nip the stresses caused by Poisson's ratio are as high, that it cannot be compensated by friction forces and slipping occurs. The resulting increase in strain leads to a corresponding decrease in strain just before the nip. Under bad conditions (high nip forces, less compressible web, small friction coefficient, small web strain at the entrance) it is possible that the strain of the web will completely decrease up to zero. In this case a bubble could arise just before the nip.

A similar situation we can find in the exit of the nip. The decrease in strain due to the stress caused by Poisson's ratio is preceded by a slip area of increasing strain. Considering the effect of the boundary condition at the nip we can see that there is no area of increasing strain if the outgoing web strain is less than the roll entering strain (curve D). Already in the case of equal in- and outgoing strain the 'swing over' of the strain can be watched (curve C). By further increasing of the outgoing strain the slip area increases (curve B) until it includes whole nip. Just the boundary condition at the nip exit has an influence on the strain development at the wrapped roll (curve A).

A variation of other parameters has shown an influence on the extension of slip and stick areas [21]. The results can be qualitatively described as follows: The slip area increases if

- Youngs modulus of the web is decreased,
- poisson's ratio is increased,
- the friction coefficient is decreased,
- the nip force is increased
- the web thickness is increased

The example 2 leads to qualitatively the same results as example 1 (see Fig. 9). The essentially decreased nip forces cause much lower changes in web strain. Because the strain increases in the entrance of the nip only just a little bit the corresponding slip zone before the nip is much shorter compared to example 1. The strains difference between the entrance and the exit of the model in the case of complete sliping in the nip is essentially reduced. To verify the numerical results we are actually developing a new measurement technology. The purpose of this measurement technology is to determine the strain rate of the web passing a wrapped roll in connection with a following nip.

CONCLUSION

The knowledge about the kinematic and dynamic process of winding is indispensible for the purposely and effectively removal of production problems and further development of machine technology into a controlled winding process. It is shown that the described method is suitable to make contribution towards the understanding of the winding process. By means of the developed systematology it will be possible in future to investigate in a convenient order winding models with increasing complexity. Thus the basic knowledge will systematically extend into the complete description of all particular effects of the total winding process.

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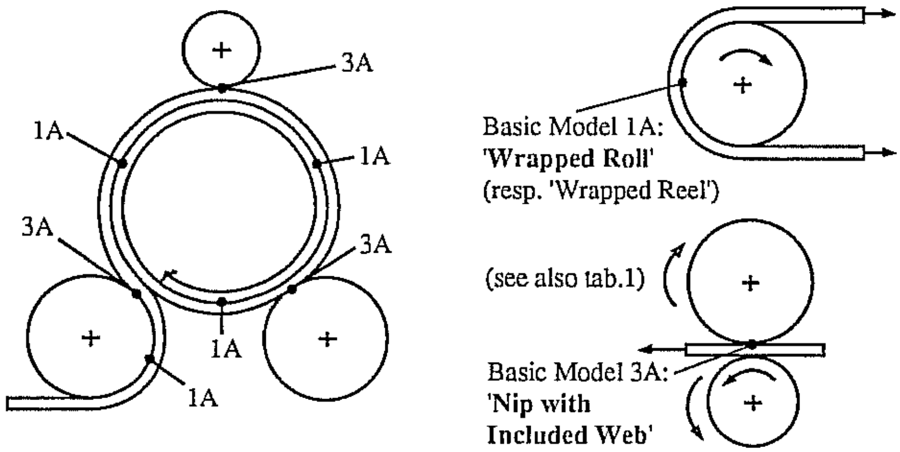

Fig. 1 Modelling of winding processes based on partial models

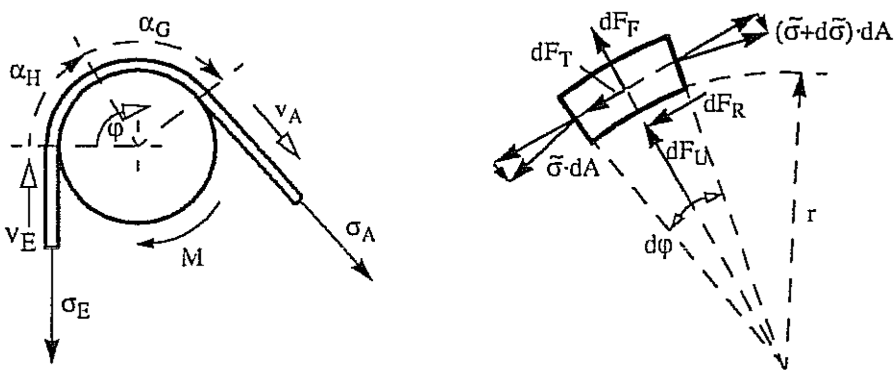

Fig. 2 Basic kinetic and kinematic idealisation of the partial model „Wrapped Roll“

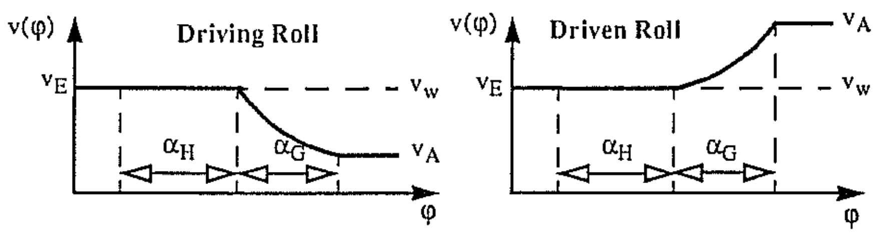

Fig. 3 Web velocity on a wrapped roll based on Capstan Formula

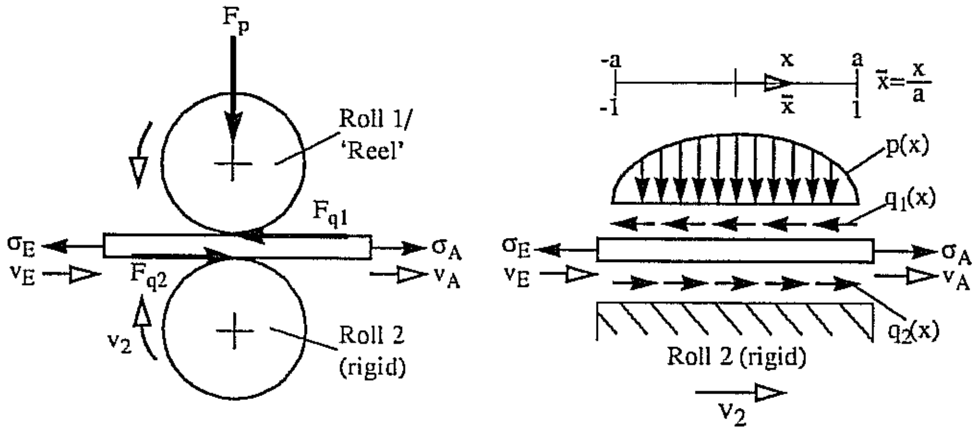

Fig. 4 Basic kinetic and kinematic idealisation of the partial model „Nip with included Web"

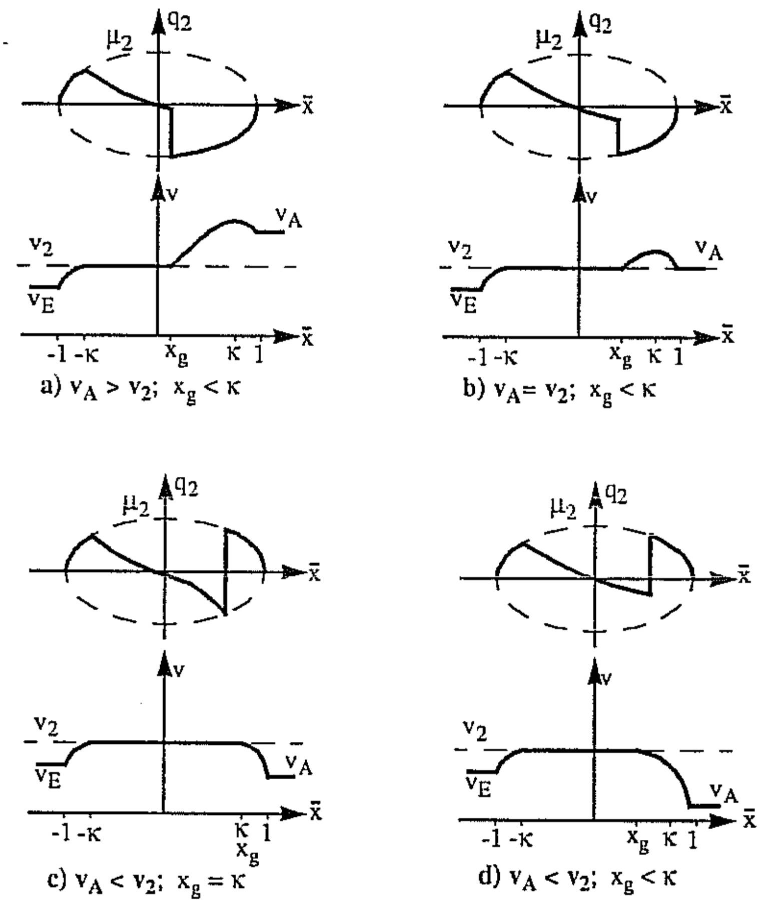

Fig. 5 Stick and slip zones in a nip for different conditions at the outgoing nip

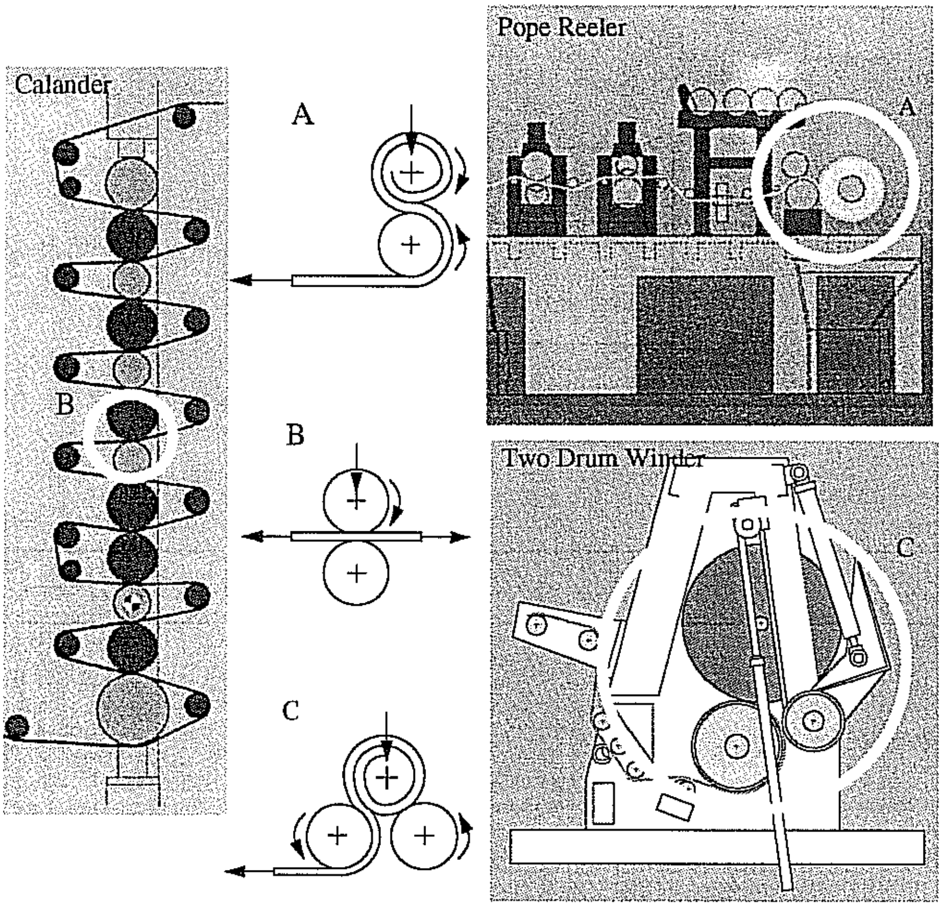

Fig. 6 Parts of paper making process idealized by coupled partial models

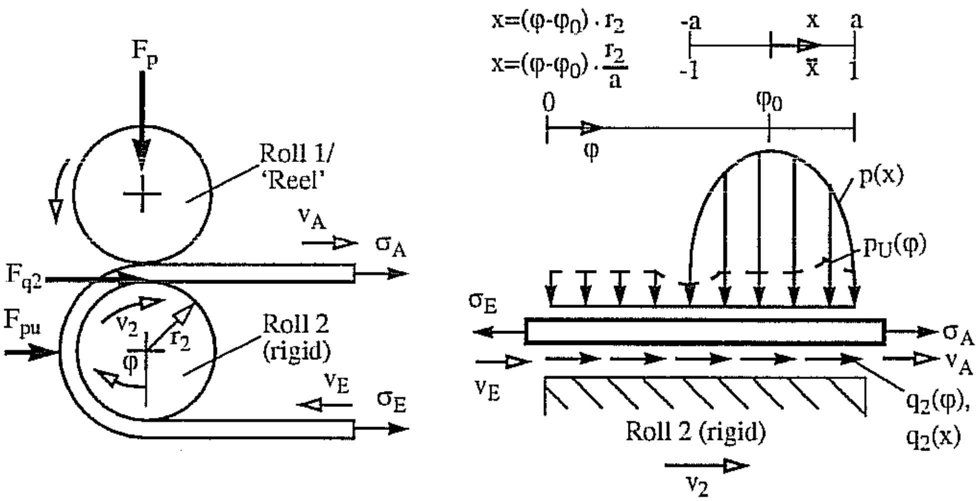

Fig. 7 Kinetic and kinematic idealisation of coupled partial models

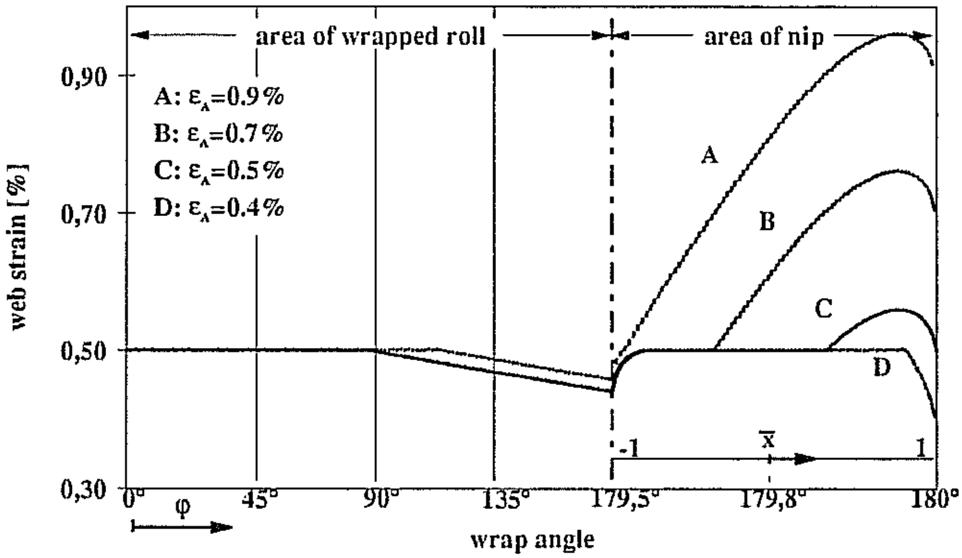

Fig. 8 Example for strain conditions in an idealized „calandering" process

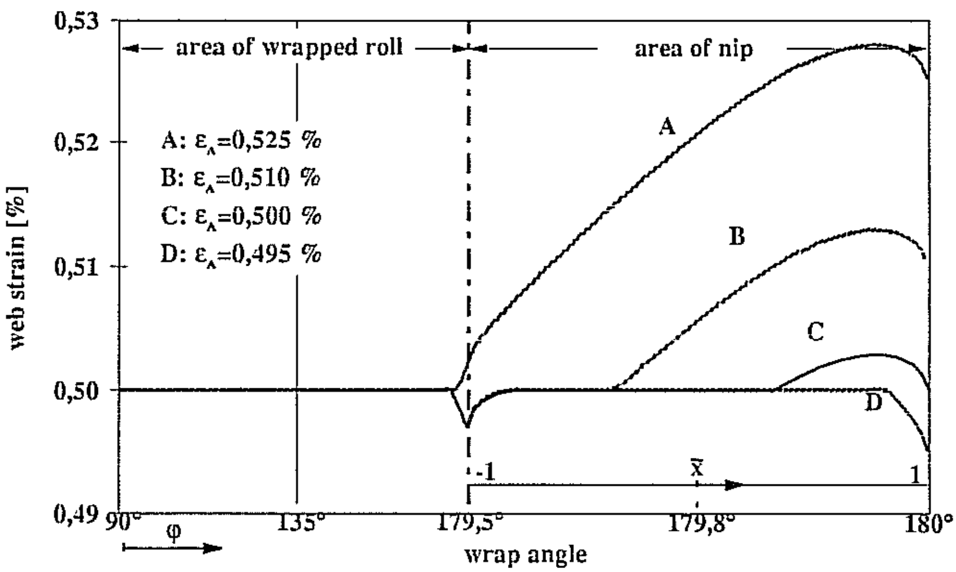

Fig. 9 Example for strain conditions in an idealized winding process

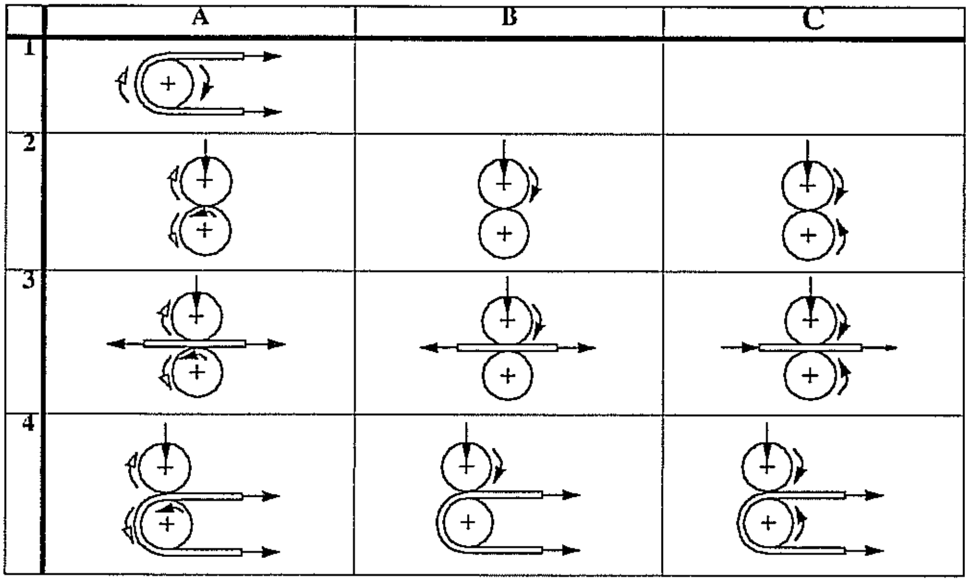

Table 1 First part of systematology of models for winding mechanics

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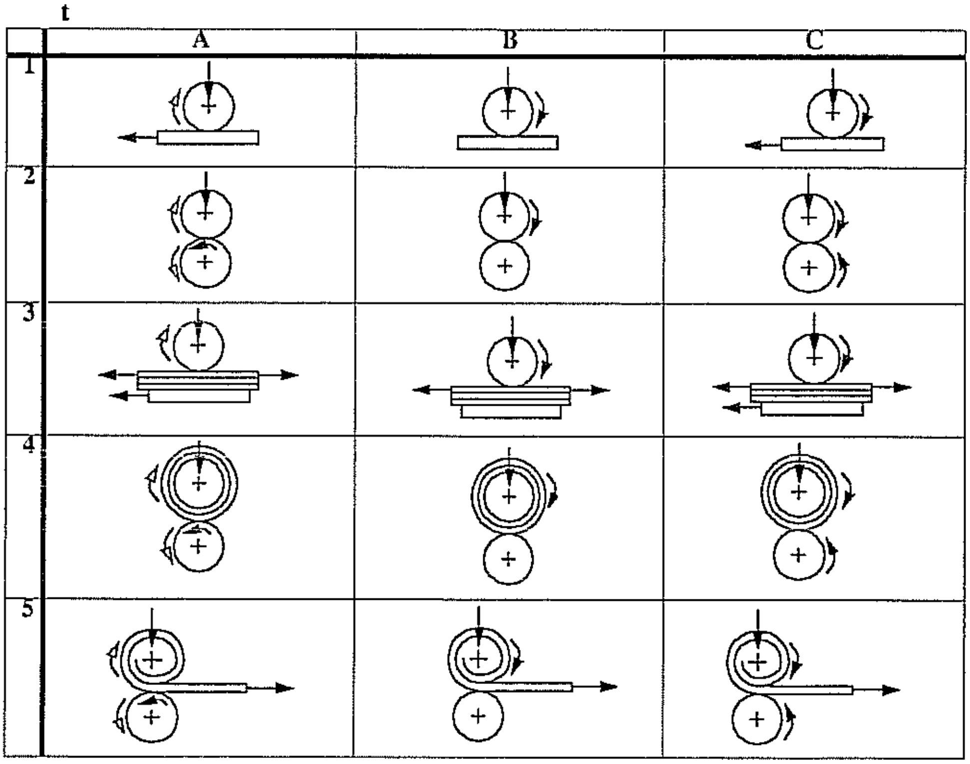

Table 2 Second part of systematology of models for winding mechanics

	$-1 \leq \bar{x} < -\kappa$	$\bar{x} = -\kappa$	$-\kappa < \bar{x} < \kappa$	$\bar{x} = \kappa$	$\kappa < \bar{x} \leq 1$
$v < v_2$	$\frac{dv}{dx} > 0$	$\frac{dv}{dx} = 0$	$\frac{dv}{dx} < 0$	$\frac{dv}{dx} < 0$	$\frac{dv}{dx} < 0$
$v > v_2$	$\frac{dv}{dx} > 0$	$\frac{dv}{dx} > 0$	$\frac{dv}{dx} > 0$	$\frac{dv}{dx} = 0$	$\frac{dv}{dx} < 0$

Table 3 Sign of the velocity gradiant as a function of partial nip zones

	Example A	**Example B**
radius (rigid) roll 2, r_2	250 mm	250 mm
web thickness, h	100 µm	100 µm
width of the nip, 2a	2 mm	2 mm
wrapping angle	180°	180°
angle of outgoing nip, φ_0	179.77°	179.77°
web starin stick zone	0.5%	0.5%
web strain outgoing nip, ε_A	0.5% - 1.5%	0.5% - 0.52%
friction coefficient (rigid) roll - web	0.08	0.08
Poisson's ratio web, ν	0.3	0.3
nip pressure, p_0	50 N/mm²	1 N/mm²
Young's modulus web in MD, E	5000 N/mm²	5000 N/mm²

Table 4 Calculation parameters for two examples in a paper making process to demonstrate the kinematic conditions on coupled partial models

Question - Were you able to verify the results of the model with experimental measurements?

Answer - No, not yet , we did not have the equipment to do this, the goal is to measure the strain and stress in vitro and submit between the roll and the reel and the method is an optical method to measure the strain and stress.

Question - Are you going to be able to measure the actual area of the slip zone? Do you think you will be able to experimentally see if that model is realistic or idealization?

Answer -I think the theoretical modeling is the first step to think about the strain and the stress situation in web, roll and nip, and also in coupled models.

Question - Your model is working only on the steady state slip and stick zones. Because of dynamics you will also get slip zones at the beginning, did you consider this in your investigation?

Answer - Not in this step of the investigation.