ON-LINE CONTROL OF TENSION IN WEB WINDING SYSTEMS BASED ON WOUND ROLL INTERNAL STRESS COMPUTATION

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ABSTRACT

One of the key challenges in the processing of flexible media such as plastic films is to obtain rolls without any aspect defect : if one considers that a "defect" (i.e. wrinkling or buckling) is due to the fact that the stress generated within the roll is greater than some "plasticity threshold", then it is crucial to predict the internal stress. Several process parameters must be carefully mastered, among which the winding tension is very important. Offline optimization of the tension can *a priori* guarantee the production of perfect rolls, with respect to the internal stress. Nevertheless, the industrial control systems never generate perfect follow-up of the tension reference value, because the tension which is actually imposed (i.e. measured) exhibits oscillations due to the imperfections of the winding system, including geometrical irregularities of the rolls. The fluctuations about the tension nominal value induce variations in the stress within the roll as compared to the value which would result from an ideal control. As a consequence, it is judicious to change the tension reference value during the winding process, according to some criterion defined from the stress computed within the roll, and then to apply this new "up-dated" reference to the forthcoming web layers. This new way of online tension control requires new concepts such as "robust multivariable control", because distributed control may not work as well.

The first step consists in computing the internal stress generated within a roll of a wound web (for instance plastic film). For that purpose, a modified non-linear model is developed in the spirit of Hakiel's. The web's winding process can be considered as a continuous accretion process, in the sense that the stress components at a given point are continuously modified by the upper superimposed layers. In addition, the residual air films which separate the web layers are taken into account in an indirect way through the radial Young's modulus of the roll which is a non-linear (polynomial) function of the compressive stress component. Several illustrative examples are presented and commented. Then, having prescribed an optimization criterion for the winding tension, an optimization algorithm based on the simplex principle is described. Finally, a new concept of *online* tension control, based on prediction-correction is proposed. Dividing the roll radius into several segments, the tension reference is computed and corrected for each range of roll radius values, by using the predictive model for the stress within the roll. The adjusted tension is reactualized step by step, following the optimization principle as described above and it will be considered as the new tension reference value for the coming layers. A comparison between *offline* and *online* tension controls clearly shows the improvement given by the new optimization technique (online).

I – INTRODUCTION

The quality of a wound roll depends on the stress state within it.

From mathematical models of the stress within a roll, we propose two methods of computing an optimized winding tension, which is used to control the whole winding chain.

The control of such systems is generally based on practical experience and the tension reference does not change during winding: see for example Reid et al [15] or Wolfermann [16]. The multivariable robust control approaches, synthesized from H_∞ and LPV techniques, have recently been studied by Koç [12]. All these control strategies can be considered as "offline tension control".

Based on the classical winding models, we illustrate the influence of the winding tension on the stress state generated within a roll.

We briefly recall the main features of "offline tension control" and we introduce the new strategy which is proposed here and that we propose to call: "online tension control".

II - BRIEF DESCRIPTION OF THE WINDING MODELS

During the two last decades, numerous papers were published in the literature, analyzing the stress state within a wound roll of a flexible medium.

The rigorous prediction of the wound roll stress started with Altmann [1]. Note that Altmann's model is based on a continuous accretion model first developed by Brown and al. [6] for planets formation. Since then, several improvements have been proposed, for example Yagoda [18] who considered adequate boundary conditions for the core and inertial effects, Connolly et al. [5] who studied the effect of external changes (temperature, humidity) on the wound roll stress state, Pfeiffer [14] and Hakiel [10] who introduced non-linear radial variation of the wound roll Young's modulus, Bourgin and al. [2-5] or Good and al. [9] who proposed to take into account the air interlayers.

II .1 - Main assumptions :

1) The web has perfectly uniform thickness, width, and length, which implies that the winding roll is a geometrically perfect cylinder.

2) The roll is a composed of concentric hoops of web.

3) The roll is an orthotropic, elastic cylinder. The cylinder is nonlinear-elastic in the radial direction : the radial modulus of elasticity is a known function of the radial stress.

4) The stress state within the roll is that of "plane stress" conditions, i.e. the stress has two components : radial and tangential. These components are functions of the radial location only.

II.2 - Basic Equations

The equilibrium equation for axisymmetrical plane stress in the presence of centrifugal forces is:

$$r\frac{d\sigma_r}{dr} + \sigma_r - \sigma_t = -\rho\left(\frac{v}{s}\right)^2 r^2 \qquad (1)$$

Where r denotes the current radius, s the outer radius of the roll, ρ is the local density and v the winding velocity.

Denoting E_t and E_r the tangential and radial Young's moduli respectively, the constitutive equations for an orthotropic cylindrical roll can be written as :

$$\begin{aligned} \varepsilon_r &= (1/E_r)\sigma_r - (\nu_{rt}/E_t)\sigma_t \\ \varepsilon_t &= (1/E_t)\sigma_t - (\nu_{tr}/E_r)\sigma_r \end{aligned} \qquad (2)$$

Now, Eq. (1) and Eq. (2) can be combined to yield the following differential equation in terms of radial stress :

$$r^2\frac{d^2\sigma_r}{dr^2} + 3r\frac{d\sigma_r}{dr} + (1-g^2)\sigma_r = -(3+\nu)\rho\frac{v^2}{s^2}r^2 \qquad (3)$$

where $g = E_r/E_t$

The two boundary conditions which are needed to solve this second-order differential equation are :

(i) Near the core, which has a modulus E_c :

$$\frac{\partial\sigma_r}{\partial r} = \left[(E_t/E_c) - 1 + \nu\right]\sigma_r + \rho\frac{v^2}{s^2} \qquad (4)$$

(ii) At the outside of the winding roll, the incremental stress caused by the last lap is :

$$\sigma_s = T_w\frac{h}{s} - \rho v^2\frac{h}{s} \qquad (5)$$

where T_w denotes the web tension and h the web thickness.

The tangential stresses are then computed by using their relation with the radial stresses :

$$\sigma_t = -\sigma_r - r\frac{\partial \sigma_r}{\partial r} + \rho\frac{v^2}{s^2}r^2 \qquad (6)$$

Finally, the total in-roll stress is obtained by adding all the contributions of the incremental stresses due to the N laps:

$$\sigma_{rtot} = \sum_{j=i+1}^{N} \sigma_{rij}, \qquad \sigma_{ttot} = T_{wi} + \sum_{j=i+1}^{N} \sigma_{tij} \qquad (7)$$

Figures 2 shows the influence of the nominal tension on the stress state within the roll. As expected, a high tension level leads to a stiff roll (larger nominal values of the tangential stress). Figure 3 shows the effect of fluctuations about the tension nominal value. Clearly, we confirm in both cases that the tension has a great influence on the stress, which means that it must be optimized during winding.

III - OPTIMIZATION OF THE WINDING REFERENCE TENSION

The concept of an "optimum reference" for controlling the web tension resorts of industrial know-how : see for instance Reid et al. [15] or Wolfermann [16-17]. The latter author proposes sensorless measurement of web tension associated with control based on fuzzy logics and neuronal networks. In most cases, we are faced with distributed control : see figure 4.

III. 1 - Offline optimization

The target of winding tension is generally determined experimentally with respect to the desired quality of the roll. This tension value can be constant or a function of the radius, according to any non linear function.

The model of stress computation makes it possible to define a criterion J by:

$$J = \int_{R_{roll}}^{R_{max}} (\sigma_\theta(T_w) - \sigma_{\theta mean}(r))^2 g(\sigma_\theta, r))dr$$

where T_w is the winding tension, $\sigma_{\theta mean}$ is some averaged value, in a given range and $g(\sigma_\theta, r)$ denotes some weight function defined by :

$$g(\sigma_\theta, r) = 1 \text{ if } \sigma_\theta \text{ is in the gauge}$$

$$g(\sigma_\theta, r) >> 1 \text{ else.}$$

The example of figure (5) shows a gauge and two curves of tangential stresses: one before optimization (a), the other one (b) computed with the new reference tension which minimizes criterion J. For both curves, the winding tension is a linear function of the radius. The optimisation algorithm is based on the principle of the simplex of Nelder and Mead [13]. Of course the convergence towards a minimum does not guarantee that it is the global minimum. In addition the existence of a solution depends on the gauge.

III. 2- New tension control strategy : online optimization of the internal stress

Offline optimization of the tension reference is supposed to guarantee *a priori* the production of a perfect roll. However, in reality, the strategies of control never generate a perfect follow-up of the instruction: the tension really applied, i.e. measured, will always present fluctuations due to the imperfections of the chains of winding and the geometrical irregularities of the roll. These tension oscillations induce variations of the stresses which would result from an ideal control, i.e. a control which would perfectly ensure the follow-up of the instruction and the elimination of the disturbances. The actual tension thus do not lead any more to the optimal stress state in the roll. It is consequently judicious to change the instructions of tension for the layers which still remain to be wound, throughout the whole phase of winding, in order to always optimize the stresses in the final roll according to the criterion as defined previously. The principle of this control is sketched in figure 6. The roll is divided into a number N of packs of layers. To describe the algorithm, let us consider time ti, which corresponds to the winding of pack i. Packs 1 to i-1 are already wound up: we know their tension reference and their actual values (measured). The instruction for i is also clearly defined and it is now possible to calculate the instruction for i+1 to N, then to compare the values of the tension measured with the ones predicted by the model for a *fictive* roll. By the gauge of the tangential stress, we will calculate the weight function. The optimization of this function by minimizing it according to the principle already defined, makes it possible to find the optimal instructions of tension for the remainder of the reel: i+1 to N. The next instructions will be thus reactualized as the roll is being wound.

The improvement is clearly illustrated in Figures 7, which present a comparison between the computed instruction offline and the instruction computed by online optimization of the stress. The latter is obtained by using a model representing an experimental device composed of three engines: winder, unwinder and tractor, Koç [12], see Figure 1. The winding tension measured corresponds to that given by the simulator, the imperfections of the sensor and the disturbances are represented by black noise. It should be noted that without the addition of this noise, the “offline” and “online” instructions remain identical.

IV - CONCLUSION

Assimilating a roll of a flexible medium (i.e. plastic film) to an orthotropic solid, the internal stress can be predicted as a function of the process conditions and of the film properties. This model is used to introduce the new concept of “online optimisation” of the reference tension : the winding tension is adjusted online so that to insure an internal stress state compatible with elastic deformations of the web within the roll. The next step would be to tailor the surface topography so that to relax the internal stress, see Boutaous *et al.* [4-5].

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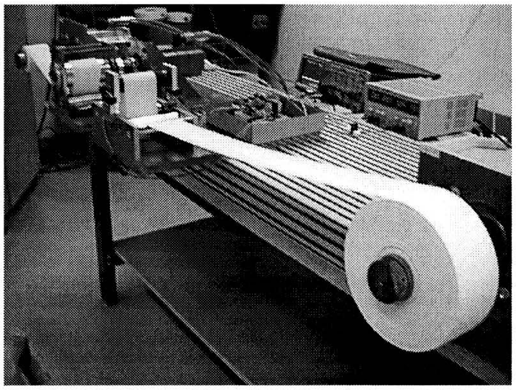

Figure 1: Chain of winding

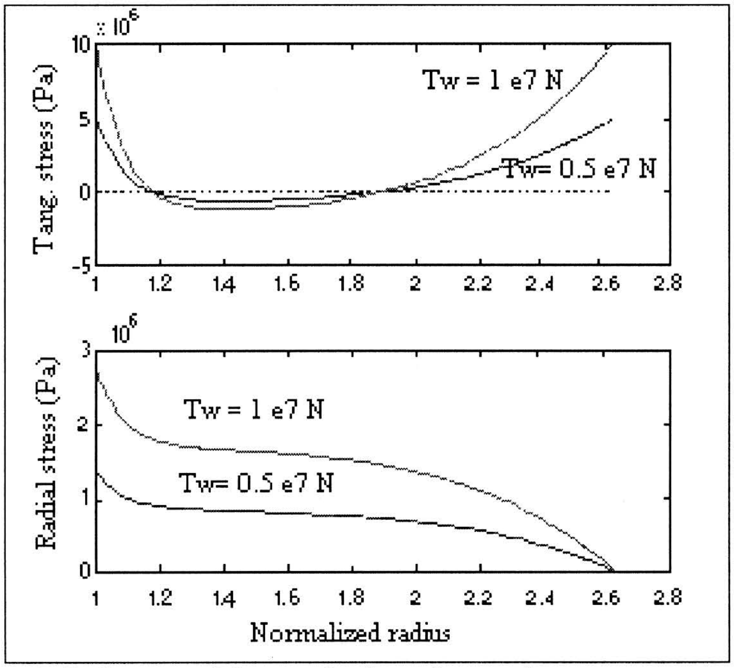

Figure 2: Influence of the nominal tension on the stress components

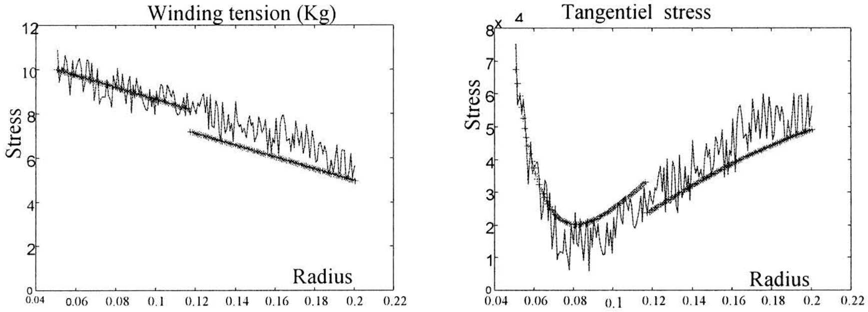

Figure 3: Effect of tension fluctuations.

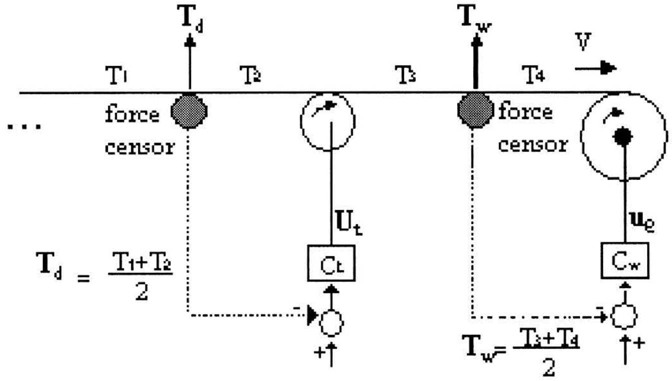

Fig. 4 : Offline optimization of the reference tension

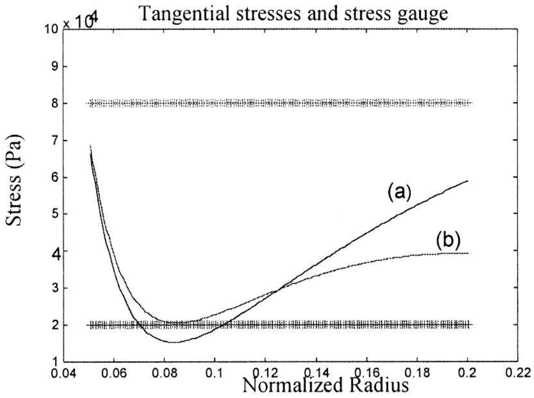

Fig. 5 : Optimization gauge for tangential stress

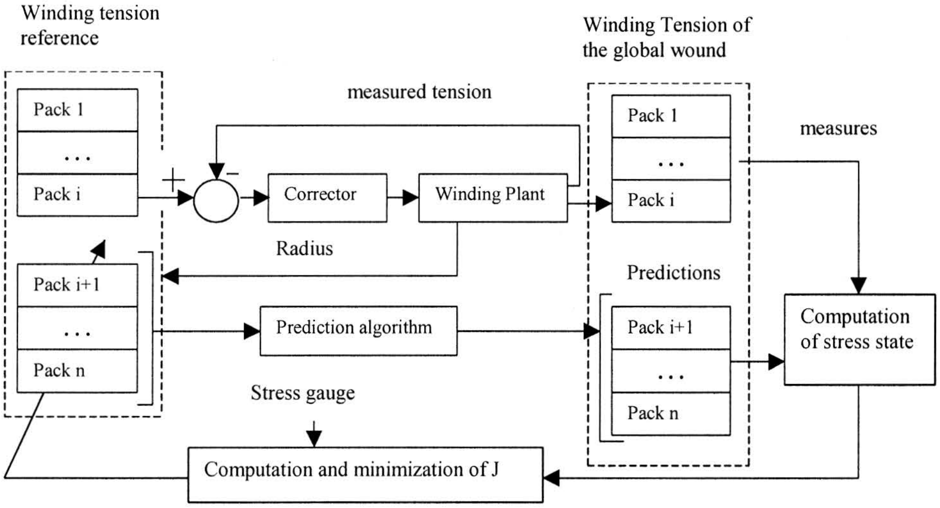

Fig. 6 : Online optimization of the reference tension

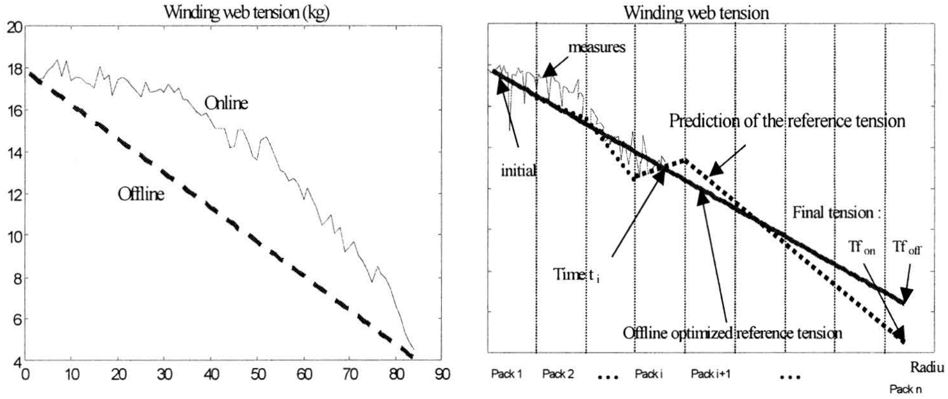

Fig. 7 : Offline and online tension references : comparison

Online Control of Tension in Web Winding Systems Based on Wound Roll Internal Stress Computation

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Name & Affiliation	**Question**
N. Vaidyanathan – Presstek	Does your optimization Criterion J have any physical significance? Does the combination of terms have any physical meaning or interpretation?
Name & Affiliation	**Answer**
P. Bourgin – Ecole Supérieure de Plasturgie	This is a classical way to define functionals that are used in optimal control. So you have a gauge where the function $g(\sigma(\theta),r)$ is equal to 1 when you are within the gauge and much greater than 1 otherwise. You search for function T_w so that functional J will be minimal. Thus there is no physical meaning for Criterion J, but this is a general way of using optimal control theory.
Name & Affiliation	**Answer (Additional)**
M. Boutaous – Ecole Supérieure de Plasturgie	This Criterion J is based on the model of Nilder and Meade. There is no guarantee that the minimum is a global minimum. It can be a local minimum. This is explained in their paper.
Name & Affiliation	**Question**
K. Shin – KonKok University	Criterion J is often used to design a controller in the control area. In your case, you have computed reference tension by use of the criteria. So you are using the criterion in a different way. Can you guarantee the performance just by calculating a reference tension? Are you using tangential stress in Criterion J or the radial stress or both?
Name & Affiliation	**Answer**
P. Bourgin – Ecole Supérieure de Plasturgie	I will answer your second question first. So far we have used the criterion only for the tangential stress. We could have used it for both (tangential and radial) but that would have led to a more complicated problem. As a first step, we decided to optimize the tangential stress which we believe is the most critical in terms of wrinkles. This is a simple, two-dimensional model. Now regarding your first question; I agree that we used the classical optimal control theory in a slightly different way. The quality of this control depends on whether we have reached a global or a local minimum. There is no way to be sure because there is no way to ensure the uniqueness of the solution. We assume that everything seems to work fine but if something is wrong, we cannot know. That is a weak point of the problem. Perhaps Dr. Koc would like to make additional comments on my answers?

Name & Affiliation	**Answer**
H. Koc – Siemens Germany	We were concerned with the control of this system. We used simple PI controllers and I will present the control aspect of this system in the paper I will present later.
Name & Affiliation	**Question**
Z. Hakiel – Eastman Kodak	Are you aware of a U.S. patent that covers the use of tangential stress models in a closed loop control system to minimize the resultant imperfections?
Name & Affiliation	**Answer**
P. Bourgin – Ecole Supérieure de Plasturgie	No, I'm not aware of this.
Name & Affiliation	**Answer**
Z. Hakiel – Eastman Kodak	I will provide you with the reference.
Name & Affiliation	**Question**
G. Homan – Westvaco	In your figure 4, you mentioned the limits you were trying to operate within: *b* is within those limits, *a* falls outside the limits. What's the difference between *a* and *b*?
Name & Affiliation	**Answer**
P. Bourgin – Ecole Supérieure de Plasturgie	The blue and red lines represent the upper and lower limits not to be surpassed. So curve *a* shows a negative part which means that in this zone there is a risk of wrinkle. Curve *a* corresponds to the stress generated without the optimization of the tension. Then using Criterion J it is possible to modify the nominal tension T_w and then curve b is obtained. So you modify the whole shape of the curve, and then the entire part of the curve is positive. This is the concept.
Name & Affiliation	**Question**
D. Roisum – Finishing Technologies	I'm surprised that you chose tangential stress as the objective function because it might predict buckling or starring, but only in conjunction with radial stress. Had you picked the radial stress, you would have been able to talk about things like telescoping and blocking and gauge bands and many other things. Maybe a wider spectrum of applications. Any comments?
Name & Affiliation	**Answer**
P. Bourgin – Ecole Supérieure de Plasturgie	Yes, you are correct. We decided to select the tangential stress as a first step for our problem. It would be better to control both, simultaneously, but this would be even more complicated. This could be one of the further steps in our research.