CONTROL AND ONLINE TENSION REFERENCE OPTIMIZATION IN WINDING SYSTEMS: APPLICATION TO AN IDENTIFIED THREE-MOTORS SIMULATOR

by

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ABSTRACT

It is well known that the tension reference value, which *a priori* guarantees a good quality roll, is based on the stress generated within the roll. However, due to the imperfections of the winding systems and to the limited performances of the disturbances rejection controllers, a control with fixed reference never generates perfect follow-up of the tension. A solution would consist in adjusting the tension reference online, according to real measurements.

In a previous paper, the criterion for tension adjustment was the tangential stress. A method for online control based on prediction-correction using the simplex algorithm was presented. This method was tested numerically.

In the present paper, we propose to generalize the criterion of tension reference optimization by considering both the tangential and the radial stress within the roll during winding. The same optimization algorithm is used, taking into account the dynamic tension model. Moreover, a dynamic gauge is now introduced, so that it can vary during the winding process. It generally represents the limits of elastic deformations of the web.

The new optimization algorithm for the on-line reference tension calculation has been validated on a dynamic non-linear winding model. This complete model used for simulations was validated on a three-motor setup using brushless motors. The setup is with PI controllers, where the web velocity is imposed by master traction motor and the tension is controlled by unwinding and winding motors.

In this approach, a new tension-prediction algorithm using a linear parameter varying (LPV) model is used. The influence of the tension prediction algorithm is also analyzed.

Several illustrative examples will be presented and the improvement as compared to an offline control will be commented.

1 INTRODUCTION

From mathematical models of the stress within a roll, we propose a method for computing an optimized winding reference 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.* [1], or Wolfermann [2] and [3].

The multivariable robust control approaches, synthesized from H_∞ and LPV techniques, has been recently studied by [4],[5],[6],[7]. All these control strategies can be considered as "offline tension control" based on the classical winding models, see for instance Geddes [8], and Jeon [9]. In this paper, we introduce a new strategy: the "online tension control".

As described in Boutaous *et al.* [10], it consists in prescribing an optimization criterion for the winding tension, given by the optimization algorithm based on the simplex principle [11]. By means of this criterion, the tension reference is computed and corrected for each range of roll radius values, by using the predictive model for the stresses within the roll. The adjusted tension is re-actualized step by step, following the optimization principle and it will be considered as the new tension reference value for the coming layers. At first, the optimization criterion is applied only to the tangential stresses [10], in this study, the criterion is generalized to both the radial and the tangential stresses.

Clearly, improvements are observed when using a static gauge, but better improvements are obtained when we use a dynamic gauge.

This on-line optimization method is then applied to a real setup of three motors winder.

2 WINDING TENSION OPTIMIZATION

Offline optimization of the tension reference is supposed to guarantee *a priori* the production of a perfect roll. However, in reality, the control strategies never generate a perfect follow-up of the reference. The applied tension thus does not lead any more to the optimal stress state in the roll. It is consequently judicious to change the tension reference for the layers which still remain to be wound, throughout all the phase of winding, in order to always optimize the stresses in the final roll according to the criterion to be defined. The principle of this online approach is sketched in figure 1: the roll is divided into a number N of packs of layers.

To optimize the winding tension reference, a mathematical model of stress computation is used to define a criterion *J*:

$$J = min\ (J_T\ , J_R) \tag{1}$$

where : $$J_T = \int_{R_{roll}}^{R_{max}} (\sigma_T(T_w) - \sigma_{T\,mean}(r))^2\, g(\sigma_T, r))dr \tag{2}$$

and $$J_R = \int_{R_{roll}}^{R_{max}} (\sigma_R(T_w) - \sigma_{R_{mean}}(r))^2 g(\sigma_R, r)) dr \quad (3)$$

T_w represents the winding tension, σ_T is the tangential stress and σ_R radial stress. The stresses are calculated using the stress state mathematical model, Bourgin *et al.* [12], Connolly *et al.* [13], or Hakiel's [14] one for instance.
σ_{mean} is some averaged tangential or radial stress value, in a given range (gauge) and $g(\sigma, r)$ denotes some penalty function defined by:

$$g(\sigma_T, r) \text{ and } g(\sigma_R, r) \;=\; 1 \text{ if } \sigma \text{ is in the gauge}$$

$$g(\sigma_T, r) \text{ and } g(\sigma_R, r) \gg 1 \text{ else.}$$

The reference tension which minimizes the cost function J is optimized using an algorithm based on the principle of the simplex presented by Nelder and Mead, [11]. Of course the convergence towards a minimum does not guarantee that it is the global minimum and not a local one. One way to overcome this difficulty would be to use "genetic algorithms". However, they are generally heavy to apply to industrial problems. One compromise here is to choose the optimization region in a pertinent way. A last remark: the existence of a solution depends on the gauge.

The criterion J is calculated for both the tangential and radial stress, and the minimum one is used to optimize the control tension.

The gauge limiting the range of the acceptable fluctuation of the stresses is fixed in the offline approach.

The gauge can be variable during the optimization process, and generally it is chosen so that to respect the limits of the elastic deformation of the wound web.

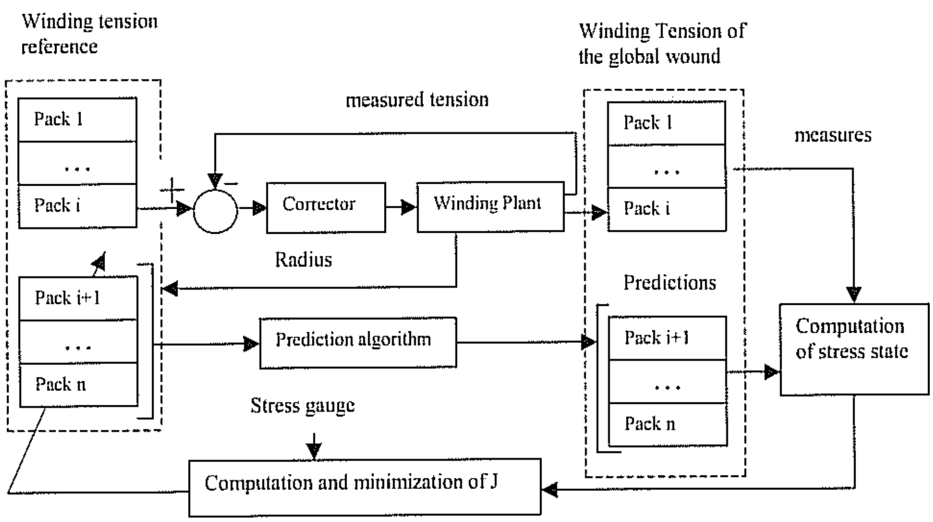


Figure 1: Online optimization of the winding tension reference

3 COMPARISON BETWEEN THE OFFLINE AND ONLINE CONTROL WITH A CONSTANT GAUGE

3.1 Perfect control:

The optimization of the winding tension for an ideal tension control, means that we have no disturbance, and the measured tension is identical to the reference (witch is in this case of study a decreasing line according versus the roll radius). For the comparison, we assume that the gauge is the same one in offline and in online optimization, and this gauge is fixed during all the process of winding. Moreover, if we impose a variable gauge, the same result is obtained: no differences between the control tensions calculated using the online and the offline methods.

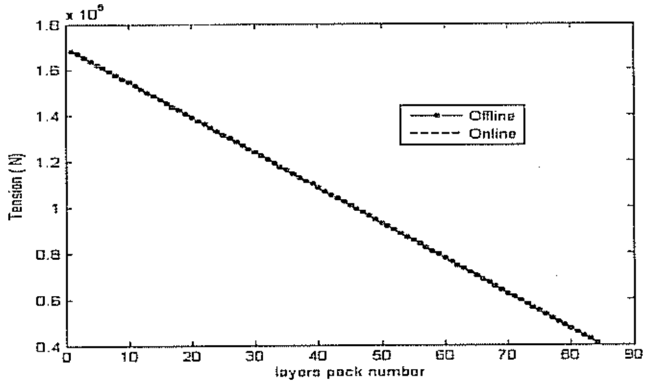


Figure 2: Offline and Online tension in an ideal control

In figure 2, it is seen that the iterative optimization (online) gives the same control tension as that obtained offline. This result is expected: it is assumed that measures and reference are the same. For the stress state calculated, (using the online or the offline optimization), as expected, we have no differences too.

Consequently, the online optimization does not make improvement in the case of a perfect system. Its contribution appears in the case of a system subjected to disturbances.

3.2 Control with perturbations in tension measurement:

Really, we are always faced to disturbed control tension. The measured tension is different from the reference one. Due to the important role witch the tension plays in the stress state within the roll during winding, see Pfeiffer [15], it is important to reject the deviations or noise by adjusting the tension during the winding process.
In figures 3 (3a, 3b, 3c), and 4 (4a, 4b, 4c), we can observe how the perturbations in the control tension affect both the radial and the tangential stress state; figure 3 for a random noise and figure 4 for sinusoidal perturbations.

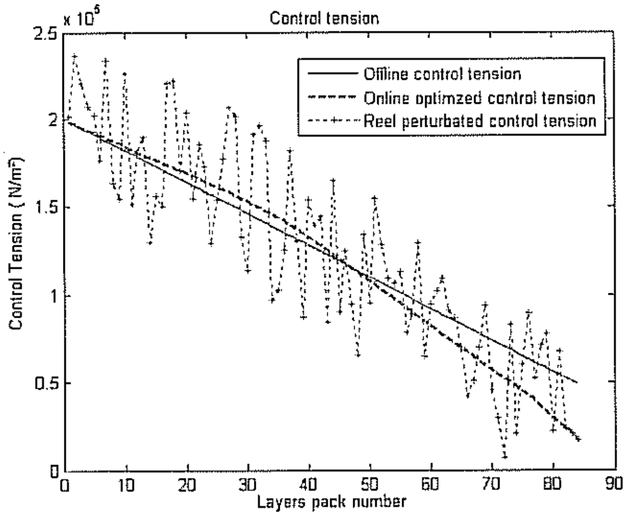


Fig. 3 a: Offline, real and optimized control tension with random noise

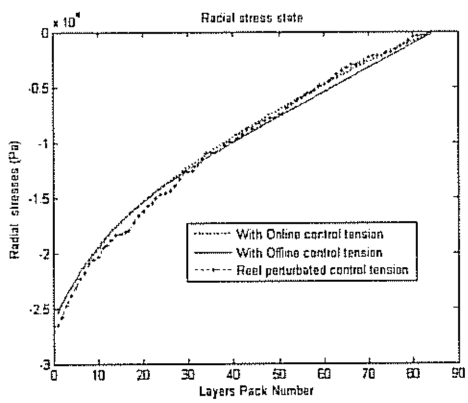


Fig. 3b: Radial stresses

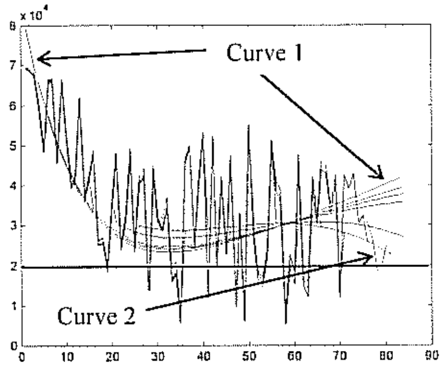


Fig. 3C: Tangential stresses

Figure 3: Offline and online optimized stresses, with static gauge.

From these figures we can distinguish two important remarks:

1- The tangential stresses are more affected than the radial stresses by the tension disturbances.

2- The stress state calculated using the offline control is different from that one calculated by mean of the online control tension.

For this example we apply a constant gauge during all the phase of optimization. Figures 3a and 4a show the comparison between the offline tension, and the tension calculated using our optimizing method, witch smoothes the perturbation and suggests an other law of the reference tension, corrected after each wound layer. This correction and prediction step by step of the evolution of the reference tension, can give us the adequate stress state, in sense of respecting the gauge values.

We can see that the online optimized reference curve is close to the "offline curve" at the beginning of winding, because the disturbances have affected only the already wound part (low number of layers), for the prediction (the remainder of the roll) we assume that there are no disturbances. As we continue the winding, the online calculated instruction deviates from that offline one. In figure 3c, various stress states are represented during the roll winding (real measurements for the already wound part, and prediction with ideal tension for the remainder to be wound). Curve 1 represents the tangential stresses of the total fictitious roll at the beginning of the process (the control tension is the offline one), and the curve 2 represents the tangential stresses at the end of winding. We observe that the perturbation affects only the wound part, but not the remainder part.

It is seen that certain stresses exceed the low limit of the gauge, and that weak variations of tension (figure 3a) generate rather large variations in the tangential stresses.

In the figures 3b, 3c and 4b, 4c, we represent the effects of the optimized tension on the stress state within the roll, compared to the one obtained using the offline tension. We clearly see that the stress state is not the same using the online or the offline control tension. In this example, we can observe that the tangential stresses in the central zone of the roll are corrected in the sense of avoiding the risk of negative tangential stresses in this zone.

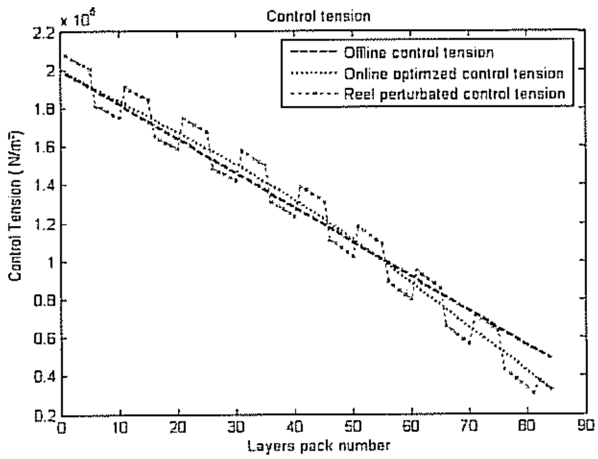
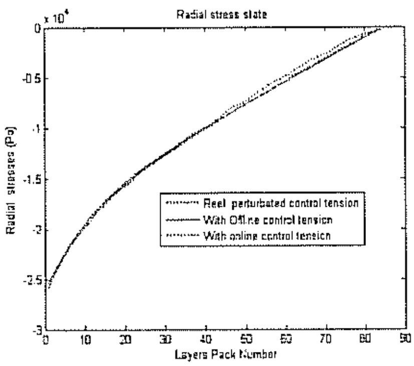


Fig. 4 a: Offline, sinusoidal and optimized control tension



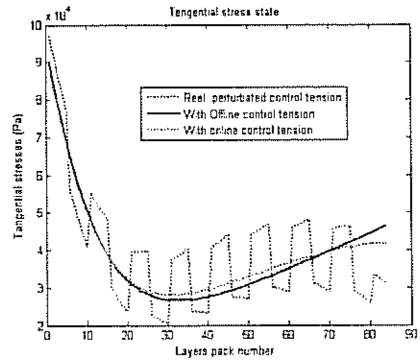


Fig. 4b: Radial stresses

Fig. 4c: Tangential stresses

Figure 4: Offline and online optimized stresses, with static gauge.

4 COMPARISON BETWEEN THE OFFLINE AND ONLINE CONTROL WITH A DYNAMIC GAUGE

In certain conditions of winding, a constant gauge is not sufficient to have a good optimization. A dynamic "variable" gauge must be applied. For example, in the central zone of the roll, we can have a negative stresses, and the quality of the roll will be altered.

One solution is to avoid this situation, by imposing a strong condition in the optimization process, by changing the value of the gauge in this zone. It is what we call, a dynamic gauge. In the figures 5 (a, b, c) and 6 (a, b, c) we have illustrated these situations, by assuming periodic simulated perturbations. In the first case (figure 5, a, b, c), the gauge used for both the tangential and the radial stresses is not constant for all the roll, but we impose that for the central zone of radius situated between the packs number 20 to 55, the gauge limits are higher than in the remainders zones. The incidence on the stress state is clearly shown. The reference control tension and the tangential stresses are very different from that computed using an offline control and a fixed gauge (figure 5). From this observation, we suggest, a way to improve the stress state in the central zone of the roll. In the figure 6, we have represented the evolution of the control tension and the stresses within the roll in case of imposing a constant gauge for the tangential stresses and a variable one for the radial stresses. In the central roll zone, the lower limit of the radial gauge is less important than in the remainder part of the roll. The result is that the tangential stresses values in this zone are upper than that obtained by means of a constant gauge and online optimization, or by means of an offline control. The opposite result is obtained by assuming a variable radial gauge for the central zone, but lower value than in the remainder zones, see figure 7 (a, b, c), i.e. the tangential stresses in the corresponding zone are upper than that obtained using the offline control. By this we can correct the stress state within the roll, when they are likely to become negative for example.

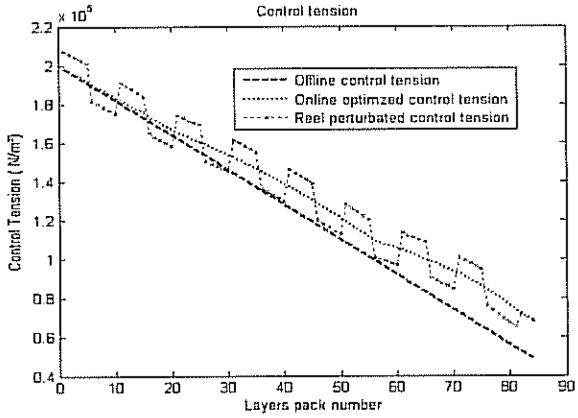


Fig. 5 a: Offline, sinusoidal and optimized control tension, with dynamic gauge between layers N° 20 to 55.

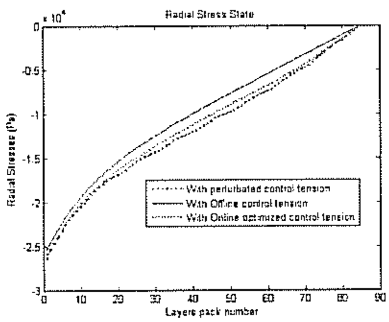


Fig. 5b: Radial stresses

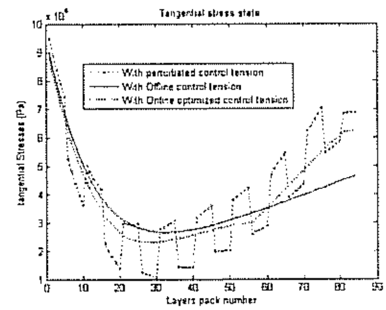


Fig. 5c: Tangential stresses

Figure 5: Offline and online optimized stresses, with dynamic gauge between layers N° 20 to 55. For this central zone, the tangential and the radial gauge limits are higher than in the remainders zones.

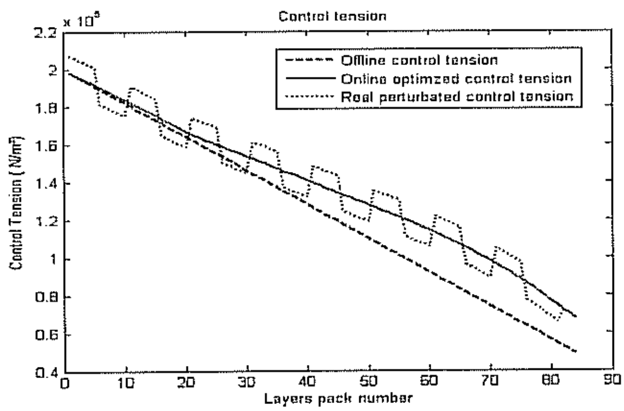
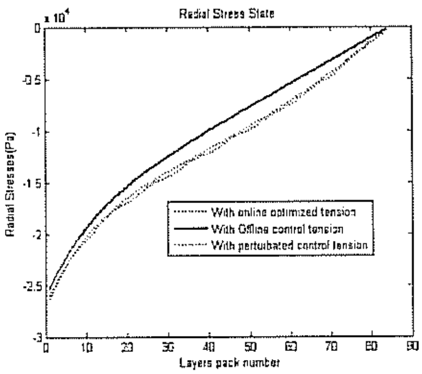


Fig. 6 a: Offline and optimized control tension, with dynamic gauge between layers N° 20 to 55.



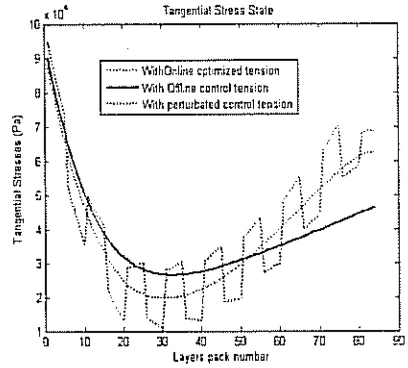


Fig. 6a: Radial stresses | Fig. 6b: Tangential stresses

Figure 6: Offline and online optimized stresses, with dynamic gauge between layers N° 20 to 55. For this central roll zone, the lower limit of the only radial gauge is less important than in the remainder part of the roll. The tangential gauge is constant.

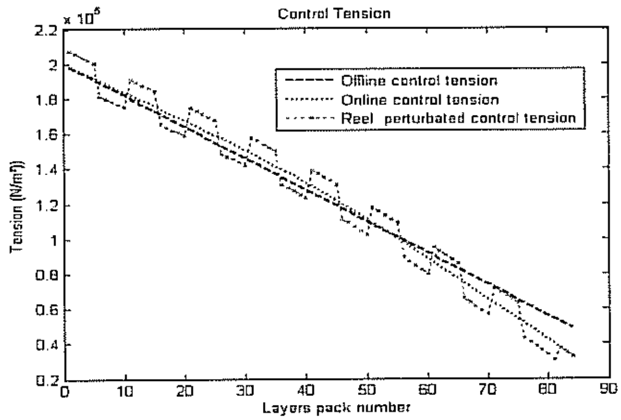
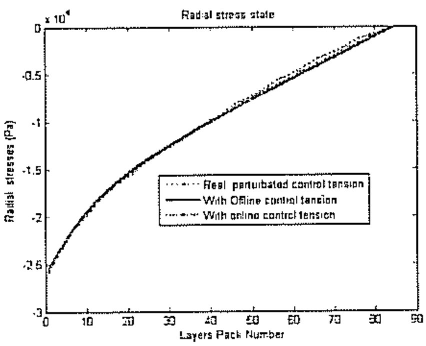


Fig. 7a: Offline and optimized control tension, with dynamic gauge between layers N° 20 to 55.



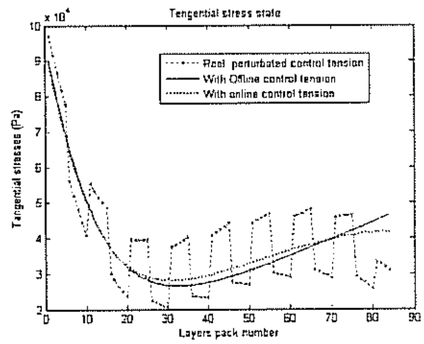


Fig. 7b: Radial stresses within the roll | Fig. 7b: Tangential stresses within the roll

Figure 7: Offline and online optimized stresses, with dynamic gauge between layers N° 20 to 55. For this central roll zone, the lower limit of the only radial gauge is higher than in the remainder part of the roll. The tangential gauge is constant.

5 ONLINE TENSION OPTIMIZATION APPLIED TO AN IDENTIFIED THREE-MOTOR SIMULATOR

For this study, we use a 3-motor nonlinear simulation model resulting from a modelling and identification of an experimental bench. The model is briefly presented; more details can be found in [4].
A scheme of a 3-motor setup with PI controllers is represented on Fig. 8. The inputs of the system are the torque control signals (u_u, u_v, u_w) of the brushless motors. The measurements are the web tensions T_u and T_w and the web velocity V.

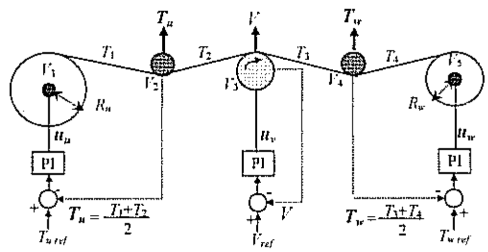


Figure 8 – Centralized control of a 3-motor plant

5.1 Plant modelling:

The nonlinear model of the web transport system is built from the equations of web tension behaviour between two consecutive rolls and the equations describing the velocity of each roll.

Web tension calculation:

The modelling of web transport systems is based on three laws, which enable to calculate the web tension between two rolls:

<u>Hooke's law</u>: the tension T of an elastic web is a function of the web strain ε:

$$T = E S \varepsilon = E S \frac{L - L_0}{L_0} \tag{4}$$

where E is the Young elasticity modulus, S the web section, L the web length under stress and L_0 the web length without stress.

<u>Coulomb's law</u>: the study of a web tension on a roll can be considered as a problem of friction between solids [4].

<u>Continuity equation</u> [4]: this equation, applied to the web, gives:

$$L \frac{dT_{k+1}}{dt} = E S (V_{k+1} - V_k) + T_k V_k - T_{k+1}(2V_k - V_{k+1}) \tag{5}$$

where V_k: represent the linear velocity of roll k.

Web velocity calculation:

The linear velocity V_k of roll k is obtained from the torque balance [4]:

$$\frac{d}{dt}\left(J_k \frac{V_k}{R_k}\right) = R_k(T_k - T_{k-1}) + K_k U_k + C_f \tag{6}$$

where $K_k U_k$ is the motor torque assumed equal to the reference value and C_f is the friction torque. Note that both the inertia J_k and the radius R_k of the unwinder and winder are time dependent and vary substantially during processing.

State space representation:

The nonlinear state-space model is composed of equation (5) for the different web spans and of equation (6) for the different rolls. Under the assumption that J_k / R_k is varying only slowly, which is the case for thin webs, V_k can be chosen as a state variable in equation (6), leading to the following linear model [6]:

$$E(t)\frac{dx}{dt} = A(t)x + B(t)u \qquad y = Cx \tag{7}$$

where: $x = \left[V_1\ T_1\ V_2\ T_2\ V_3\ T_3\ V_4\ T_4\ V_5\right]^{\mathrm{T}}$, $y = [T_u\ V_3\ T_w]^{\mathrm{T}}$ and $u = \left[u_u\ u_v\ u_w\right]^{\mathrm{T}}$.

5.2. Simulations :

The figure 1 represents the online optimization principle of the winding tension reference.
In our case, the plant is substituted by the non linear model, while the LPV (linear parameter variant) model (equation 7) is used for the prediction algorithm.

Figure 9 represents the winding tensions:

- in dashed line: the off line optimized tension reference
- in disturbed line: the tension really applied to the roll during the winding process. It should be noted that during winding, we changed the linear velocity of the web according to figure 10. The variations of tension come from the coupling to the velocity. We are thus in the presence of a tension really applied which differs from its reference one.
- in continuous line: the optimized online reference tension with the real tensions (in our case using the non-linear model) applied to the roll. We observe clearly that this curve differs from that obtained by the offline control.

In the figure 11 we have represented:

- The stresses computed using the offline reference tension, applied directly to the roll, by assuming that we have a perfect control and thus a perfect follow up of the reference.

- The stresses computed using the real applied tension, with the tension issued from the non linear simulator for the online optimized reference tension.

From these figures, we have shown that the suggested online method can be applied to real winding systems. Therefore, this method can be considered as solution for the winding control, when the offline methods are not sufficient.

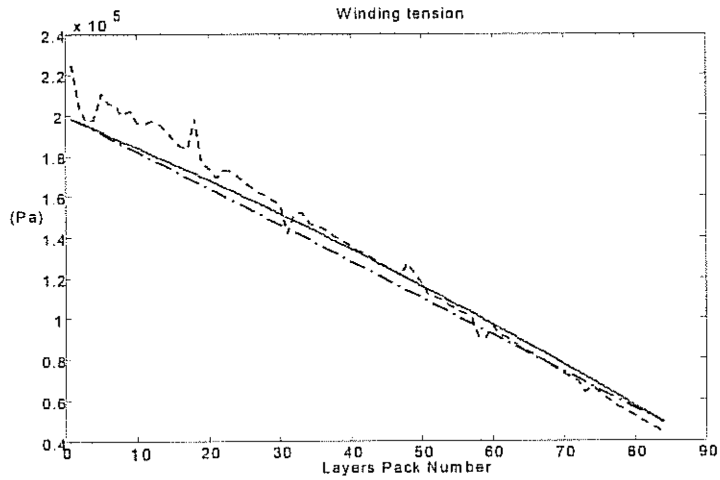


Figure 9: Winding tension versus the roll radius

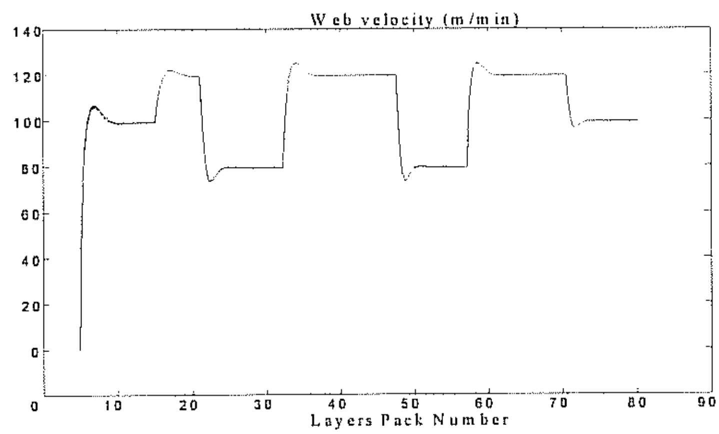


Figure 10: Web velocity during winding

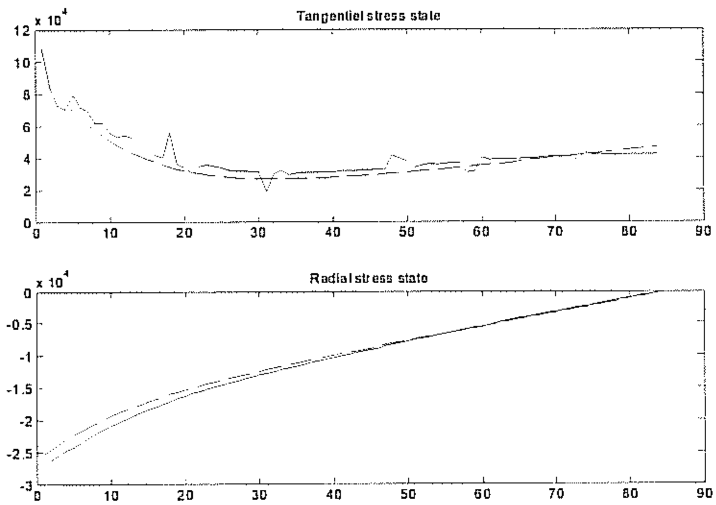


Figure 11: Tangential and radial stresses using offline and online control.

6 CONCLUSION

Because the web tension acts directly on the stress state within a roll, it is very important to master and to optimize it during the winding process.
To do, a mathematical model calculating the stress state within a roll is used to optimize the tension reference during the roll winding.
A new optimization strategy called "online optimization" is used and compared to the classical "offline" one. The comparison shows interesting improvements, in terms of insuring an internal stress state compatible with elastic deformations of the web within the roll.
This method, associated to a dynamic gauge, presents an interesting way to optimize the reference tension in winding systems. The application of this method to a 3-motor plant simulator confirms its applicability to real systems and the real optimization alternative witch it represents when the offline methods are not sufficient.
The next step consist in improving the stress calculating model, by taking into account really the role of surface topography, Boutaous [16], Good *et al.* [17].

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Control and Online Tension Reference Optimization in Winding Systems: Application to an Identified Three-Motors Simulator

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Name & Affiliation	Question
Neal Michal Kimberly-Clark	It looked like your radial pressure profiles were backwards. The pressure was maximum at the outside of the roll and minimum at the inside. Is this correct?
Name & Affiliation	**Answer**
M. Boutaous INSA site de Plasturgie	The magnitude of all the radial stresses (in Figures 3b, 4b, 5b, 6a, 7b and 11) in the paper decrease as the roll radius increase. Notice that the y axis lower limit is a negative number and the upper limit is zero.
Name & Affiliation	**Question**
Mike Madaras Goodyear Tire & Rubber	Is this technique just applicable for center driven winders or can you apply it to two-drum winders? You show the center driven arrangement but can you use the same technique for another winder type?
Name & Affiliation	**Answer**
M. Boutaous INSA site de Plasturgie	Yes, this technique is applicable to different types of winding. I just showed the central winding case.
Name & Affiliation	**Question**
Calixto Estrada Dupont	When you make reference to future work, you referred to surface topography. Does that mean inter layer friction effects?
Name & Affiliation	**Answer**
M. Boutaous INSA site de Plasturgie	Yes, that is one effect but the surface topography also be integrated into the stress computation models, by introduction of air entrapment. The roughness of films plays an important role in the rate of the interlayer air film exhaust.
Name & Affiliation	**Question**
Vincent Chen Procter & Gamble	Concerning your optimized tension profile. The profile in Figure 6b has a very stair-stepped nature. The variation in tension looks to be very large. It has about a 15,000 Pascal jump. Is there a way to minimize that variation?
Name & Affiliation	**Answer**
M. Boutaous INSA site de Plasturgie	It is well known that we have direct relationship between the reference tension and the stresses generated within the roll. For this reason, the profiles (figure 6b) have very stair-stepped natures as in the tension profile. To minimize the magnitude of the variations the control tension must be optimized. In the case of this study, the variations are strongly accentuated for the need of the

simulation.

Name & Affiliation	**Question**
Vincent Chen Procter & Gamble	Do your input have a square wave shape?
Name & Affiliation	**Answer**
M. Boutaous INSA site de Plasturgie	It is just a numerical simulation. I assumed a square wave variation in the tension to simulated noise. Due to the relationship between the tension and the stresses, the same square shape is found in the stress profile. This is just an example of one noise type, but you can consider any different shape.