WEB TENSION CONTROL IN AN INDUSTRIAL ACCUMULATOR

by

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ABSTRACT

This paper presents the study of an industrial accumulator used in a web transport system. In order to understand the main characteristics of the accumulator and the causes of problems appearing during transient phases, different models based on physical laws have been built.

Different approaches are tested to calculate the web tension between two rolls. The selected approach uses an empirical law to express the web tension as a function of the downstream span tension and the difference of velocities between consecutive rolls. The empirical law aims to respect the mechanical behavior and the tension and velocity conditions imposed at the entry and the exit of the accumulator, which is not realized in classical web transport modeling.

One actuator is available to maintain the web tension approximately constant in the whole accumulator during the accumulator descent. Experiments and simulations have permitted to show that the existing industrial PI control of the web tension is not very satisfactory. The comparison of the PI control with a multivariable control (H_∞ robust control) is presented. To improve the accumulator operation, new approaches are suggested, such as modifying the input parameter or introducing a mechanical tension regulator.

NOMENCLATURE

α	tunable constant used in the model identification
E	Young modulus
E_V	elasticity parameter
E_{V0}	nominal elasticity parameter

ε	web strain
J	roll inertia
K	robust controller
L	web length between two rolls
μ	friction coefficient
N	total number of rolls in the accumulator (N=44)
ν	viscosity modulus
R	roll radius
s	Laplace operator
S	web section
θ	rolling-up angle
T_k	web tension between roll (k-1) and k
T_0	nominal web tension
T_1	tension measured on the load cell placed on the 1st bottom roll
T_{21}	tension measured on the load cell placed on the 21st bottom roll
T_{k_inf}	inferior tension allowed on the load cell placed on the kth bottom roll
T_{k_sup}	superior tension allowed on the load cell placed on the kth bottom roll
V_k	velocity of the roll k
V_{accu}	accumulator descent or ascent velocity ($V_{accu} = dL/dt$)
ω	frequency

INTRODUCTION

Many plants producing plastics, papers or metals have continuous processing lines with running webs on driving machines (figure 1). For a web transport system, the main concern is to prevent the occurrence of breaks. The break of a web causes the line to stop, resulting in a waste of time, and a lower productivity.

The accumulator in a web transport system allows the soldering of the webs from two different rollers while furnishing enough web during this process so as to maintain a constant velocity at the output of the accumulator.

The web tension in the accumulator is perfectly controlled during normal operation, e.g., when the accumulator height is stable. But, during the descent and ascent phases of the accumulator, the web tension could drop which can cause folds and web shift resulting in line stops. The web tension could also rise and even generate folds or breaks. The derivation of a mathematical model of the accumulator allows the use of a less empirical approach to the control of this process and gives us a better understanding of the influence of each parameter.

The model can also be used for the elaboration of other control strategies, which can then be validated in simulation before being implemented on the production line.

Generally, the knowledge in the domain of web transport systems is in the industrial know-how. The scientific literature is essentially about horizontal web traction systems, (see [1], [2], [3] [4] and [5]) or winding and unwinding systems, (see [6] and [7]). Only few authors deal with accumulators, and in the case of, it is often metal strip transport systems (see [8]).

This paper presents the process description, its model and its identification. Then, the control of the accumulator is studied by comparing two controllers. Finally, performance improvement strategies for the accumulator operation are presented.

PROCESS DESCRIPTION

The industrial accumulator under study is composed of 22 rolls on top and 22 rolls on the bottom (figure 1). The 22 upper rolls can be moved vertically thanks to a motor that moves the base supporting them. A web driving motor is put at the entry and another at the exit of the accumulator. Force detecting sensors are put on the bottom rolls 1 and 21, in order to measure the web tension at these points. Additionally, some bottom rolls are driven by torque controlled motors that are aimed to facilitate the web transport by compensating the friction.

PROCESS MODEL

The model should provide web tension and roll velocity in all parts of the accumulator. For that purpose, the system is modeled by sections (cf. figure 2). The web tension and roll velocity of a section are function of the tension and velocity of the next and previous sections.

Velocity calculation

A torque balance on the roll gives (see [6]):

$$\frac{J}{R}\frac{dV_{k-1}}{dt} = R(T_k - T_{k-1}) \qquad \{1\}$$

A model with friction and motor torque shows that their effects are negligible in the dynamics. We modify this classical equation by limiting the tensions to zero when they become negative. This is due to the fact that negative web tensions produce folds of the material (essentially, in the case of polymers), and no torque is applied to the roll.

Tension calculation

First approach: driving belt systems. The conditions for web sliding or sticking on the roll are distinguished by the use of Coulomb friction laws. The Capstan formula expresses a relation between the output and input web tensions on a roll ([1] and [9]), see also figure 3.

in sliding mode: $T_k = T_{k-1} \exp(\pm\mu\theta)$ {2a}

in sticking mode : $T_{k-1} \exp(-\mu\theta) \le T_k \le T_{k-1} \exp(\mu\theta)$ {2b}

The web sticks to the roll as long as the sticking condition {2b} is fulfilled. If this condition is not verified, which can occur during transient phases of the accumulator descent, the mode switches into sliding mode and the output tension is computed with the formula {2a}. The condition to switch back in sticking mode is the equality between web velocity and roll velocity. See figure 4 for the principle of calculation.

The web elasticity is neglected in this model. The next step is to build a model taking web elasticity into account, in order to investigate which phenomenon is predominant: sliding and sticking modes or web elasticity.

Second approach: web elasticity and mass conservation. The Voigt model expresses the tension for a visco-elastic material as a function of the web strain[10]:

$$T = E.S.\varepsilon + \nu.S.\frac{d\varepsilon}{dt} \qquad \{3\}$$

Associating the mass conservation law to Voigt's law for a linear material, a relation between tensions and velocities for two successive rolls can be found [7]:

$$\frac{d}{dt}\left(\frac{L}{1+\frac{T_k}{E.S}}\right) = \frac{V_{k-1}}{1+\frac{T_{k-1}}{E.S}} - \frac{V_k}{1+\frac{T_k}{E.S}} \qquad \{4\}$$

A simplification of this relation, for small variations of velocity and tension, gives (see [11]):

$$T_k - T_{k-1} = \frac{E.S.(V_k - V_{k-1} - V_{accu})}{V_{k-1}(1+\frac{L}{V_{k-1}}s)} \qquad \{5\}$$

The main assumptions used for this modeling are:
- the roll velocity is equal to the web velocity.
- the friction torque are supposed to be compensated by torque controlled motors.

The first and second approach used together by Brandenburg are presented in [9]. The resulting model is quite complex and the friction coefficients become time constant in the final equation. Often this approach is used to determine sliding conditions of the web on a roll. Moreover, as all the parameters corresponding to the friction coefficients are empirical and difficult to identify, and since the web sliding conditions present a secondary problem for our study, no model were built from this approach.

A recurrence is established to compute the tension, by using the equations {2a}, {2b} and {1} for the first approach and {4} and {1} for the second approach.

For both approaches, the input tension and the output velocity have to be imposed. However, for the accumulator, it is very important to impose the input velocity (the web must not move during the soldering). Moreover, the input tension cannot be known during the soldering. Consequently, the recurrence relations cannot be used, since the limit conditions are not fulfilled. Therefore, an empirical law is defined in order to obtain a model adapted to the accumulator.

Since, the results obtained with the first approach do not show the dynamic variations of the tension, the empirical law is defined using the same assumptions as in the second approach.

Third approach: empirical tension calculation. This relation has been derived empirically, by adjusting the response of the model to be as close as possible to the behavior of the real accumulator and by analogy with equation {5}:

$$T_k = T_{k+1} + E_v\left(V_k - V_{k-1} + V_{accu}\right) \qquad \{6\}$$

(a) Clearly, T_{k+1} is dependent on T_k due to the transmissibility of the tension [2]. This model assumes that T_k can be derived from the knowledge of T_{k+1} .

(b) The second term expresses the fact that the tension variations are due to the velocity differences between two consecutive rolls. The elasticity parameter E_V is not constant but is calculated as a function of the tension, using another empirical equation:

$$E_v = \exp\left(\alpha \frac{T_k - T_0}{T_0}\right) E_{v0} \qquad \text{and} \qquad E_v \leq E_{v0} \qquad \{7\}$$

This equation expresses the fact that, the influence of the velocities on the tension variations is smaller with smaller tension. This can be explained more particularly for polymers by the web visco-elasticity and by the fact that the roll drive is less effective with smaller web tension. For example, if $\Delta V = V_{k+1} - V_k$ produces a tension drop of $\Delta T = 60$ *N* when the nominal tension is 100 N, then the same ΔV can only produce a drop of 40 N when the nominal tension is 40 N.

IDENTIFICATION

The identification is done by minimizing the mean square error between the measured and simulated tension for both roll 1 and roll 21 (see also [12]).

We can observe both on the measured and simulated curves the problems appearing during the transient phase of the accumulator descent (see figure 5): the tension falls at the exit (roll 21) and the tension rises at the entry (roll 1). The difference of the peak value between simulation and measurement on the roll 1 is due to the sensor saturation at 300 N. When the sensor indicates a very small web tension, web folds are observed on the real system. Measurements have been done on the real system for a descent accumulator using the tension correction for the descent velocity. This explains the fluctuations on the accumulator velocity in figure 5.

It can be concluded that this model produces a very good approximation of the tensions on the rolls 1 and 21.

Rolls inertia influence

The way the roll inertia influences the web tension has been studied by simulating the tensions on the rolls 1 and 21 for three different inertia as illustrated in figure 6. The smaller the inertia, the faster the system responds. Thus, the web fold duration at the accumulator exit is shorten. The roll inertia has little effect on the accumulator entry tension.

ACCUMULATOR CONTROL

Existing industrial regulation

During the accumulator descent the entry motor is stopped, the exit motor velocity is maintained, and the accumulator motor (REG ACC in figure 7) is used to lower the upper rolls and correct the tension on the roll 21. Therefore, we are interested in REG ACC to study the accumulator control.

The goal of the existing industrial regulation is to suppress the tension drop on the roll 21 using a PI controller. It has been observed (see figure 8) that the larger the controller gain, the smaller the tension drops, but also the larger the tension rises on roll 1 (and on roll 21 after the tension drop).

Robust controller synthesis

The velocity variations of the entry motor and the accumulator descent are disturbances for the web tension in all the accumulator. The H_∞ robust controller K aims to limit the transfer of the velocities to the tensions ($\mathbf{T}_{y1u1}$) [13] (see figure 9):

$$\min_{K}\left\{\left\|\mathbf{T}y_1u_1\right\|_\infty := \sup_{\omega}\sigma_{\max}\left(\mathbf{T}y_1u_1(j\omega)\right)\right\} \qquad \{8\}$$

A simplified dynamical model of the accumulator is built to compute the H_∞ robust controller. This multivariable model is made of transfer functions of the following type:

$$TF = \frac{b_1 s + b_0}{a_1 s + a_0} e^{-T_{delay} s} \qquad \{9\}$$

Where a_0, a_1, b_0, b_1 and T_{delay} are identified by minimizing the mean square error between the accumulator complete non linear model response and the simplified model response.

Then, the H_∞ robust controller is computed via γ-iteration [13][14] (algorithm of Glover / Doyle), after adding frequency weighting filters at the inputs and outputs of the model.

Comparison between controllers

Before comparing the results from two controllers, a penalty / barrier function approach is used to find the optimal controller. A cost function F_{cost} including penalization coefficients (p_1 and p_{21}) is defined:

$$F_{\text{cost}} = \int\left(p_1\left(T_1 - T_0\right)^2 + p_{21}\left(T_{21} - T_0\right)^2\right)dt \qquad \{10\}$$

where p_1 and p_{21} are defined as follows:

if $T_1 < T_{1\_sup}$ $p_1=1/100$ otherwise $p_1=10000$;

if $T_{21\_inf} < T_{21} < T_{21\_sup}$ $p_{21}=1$ otherwise $p_{21}=10000$;

where $T_{1\_sup} = T_{21\_sup} = 500$ N, $T_{21_inf} = 25$N.

The main concern is to bound the maximum tension (to prevent web breaking) and the minimum tension (to prevent the web to come unstuck from the roll and so to be shifted to the sides) on roll 21, ensuring in this manner a good transport for the rest of the line. As the web is stopped on roll 1, the small tension does not present any web shift risk at this point.

The use of a multivariable controller, as the H_∞ robust controller, improves slightly the web tension control (see figure 10). The peak of the tension T_{21} is decreased and the minimum is increased. And roughly the same performance is obtained for the tension T_1.

Regulator performance improvement

It is difficult to find a good tradeoff by correcting only the accumulator descent velocity. If the tension rise on roll 1 could be avoided, the regulation of the tension on roll 21 would be easier. A solution to reduce this tension rise consists in reducing the stop velocity slope of the entry motor. The drawback of this solution is that it raises feasibility problem for the industrial application. This problem comes from the fact that it is quite difficult to estimate the length of the web to be unwounded (see figure 1) to stop the entry motor. The simulation is shown on figure 11 with a PI regulator.

New type of accumulators: mechanical tension control

An alternative for improving the control strategy for the accumulator, consists in improving the mechanical design of the accumulator. The new type of accumulator we propose, should be able to suppress the tension drop at its exit and the tension rise at its entry. It can be realized by replacing one or more rolls of the accumulator by dancing rolls. This modification implements a mechanical regulation of the tension and gives very interesting results.

Simulations have been done for different configurations and the best results were obtained by placing one dancer close to the entry (on the 3rd roll) and another close to the exit (on the 17th roll) of the accumulator. With this configuration the exit tension drop is filtered out, and the entry tension rise is decreased with a maximum dancer position variation of about 1m. The figure 12 shows the results obtained with a PI controller.

CONCLUSIONS

The particular operating conditions of the accumulator led us to establish a new mathematical description which takes into account the conditions imposed on the accumulator. The model obtained can be used to study the effect of different component characteristics (roll inertia, roll radius, helper torque, ...) before building an accumulator. It can also be used to test the efficiency of existing control strategies as well as of new types of controllers.

The first technique to improve the accumulator operation consists in changing the control method. The improvement obtained with a H_∞ controller is significant but not totally satisfactory.

To further improve the results with the same control strategy, the input parameter of the system should be modified.

Finally, it is also possible to improve the accumulator performances by adding a mechanical regulation system that includes dancers in the accumulator. Even though, this mechanical control system seems very interesting, it may be difficult to implement on a new or an already existing system.

ACKNOWLEDGEMENT

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REFERENCES

[1] Zahlan, N., and Jones, D.P., "Modeling web traction on rolls", Proc. IWEB3, Oklahoma, pp. 156-171, (1995).

[2] Shin K.H., "Distributed control of tension in multi-span web transport sytems", Doctoral thesis, Oklahoma State University, (1991).

[3] Brandenburg, G., "Über das dynamische Verhalten durchlaufender elasticher Stoffbahnen bei Kraftübertragung durch Coulomb'sche Reibung in einem System angetriebener, umschlungener Walzen", Doctoral Thesis, Technischen Universität München, (1971).

[4] Reid, K.N., Shin, K.H., and Lin, K.C., "Variable-gain control of longitudinal tension in a web transport system" AMD, Web Handling, ASME, pp. 87-100, (1992).

[5] Wolfermann, W., "Tension control of webs - a review of the problems and solutions in the present and future" Proc. IWEB3, Oklahoma, pp. 198-229, (1995).

[6] Olsen, J.E., "Theoretical Analysis of winding mechanics". PhD Thesis, Norwegian University of Science and Technology, (1996).

[7] Wolfermann, W."Mathematischer Zusammenhang zwischen Bahnzugkraft und inneren Spannungen beim Wickeln von elastischen Stoffbahnnen", Doctoral Thesis, Technischen Universität München, (1976).

[8] Parant, F., "Modélisation et identification d'un système fortement oscillant, application à l'entraînement de bande de métal", Doctoral Thesis, Institut National Polytechnique de Lorraine, Nancy, (1990).

[9] Brandenburg, G.," Ein mathematisches Modell für eine durchlaufende elastische Stoffbahn in einem System angetriebener, umschlungener, Walzen" - Regelungstechnik und Prozess-Datenverarbeitung, Vol. 3, Part 1, 2, 3, (1973).

[10] Pakka, P., Ryymin, R., Kurki, M., and Taskinen, P., "On the dynamics of web transfer in an open draw", Proc. IWEB3, Oklahoma, pp 117-134, (1995).

[11] Boulter, B.T., Gao, Z., "Matrix interpolation based self-tuning web tension regulation." Proc. IWEB3, Oklahoma, pp. 280-300, (1995).

[12] Koç, H., Knittel, D., Gauthier, C., Abba, G., Ostertag, E., "Modeling and identification of industrial accumulator in an elastic web transport system", CESA98 Computational engineering in systems applications, Tunisia, pp 403-407, (1998).

[13] Zhou, K., Doyle, J, and Glover, K., "Robust and optimal control", Prentice Hall, Upper Saddle River, New Jersey, (1995).

[14] Chiang, R., Safonov, M., "Matlab Robust Control Toolbox", The Math Morks Inc., Natick, (1992).

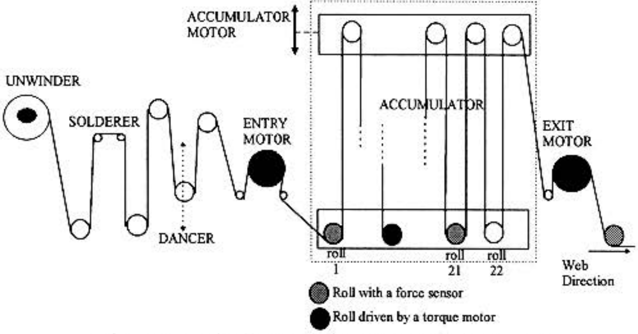
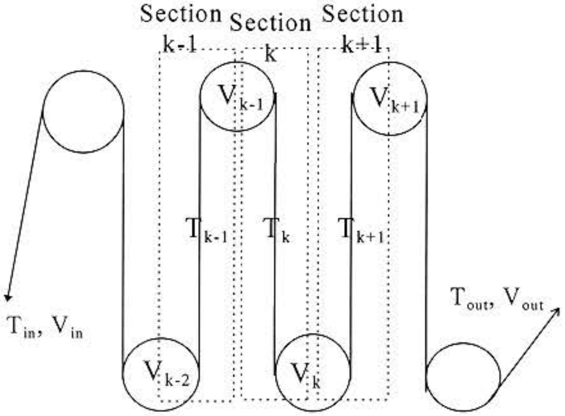


Fig. 1 Unwinding system and accumulator



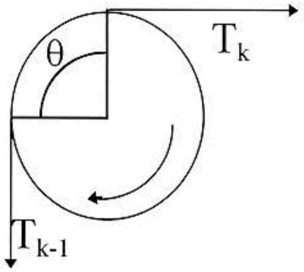


Fig 3 - A roll input and output tension

Fig 2 - Modeling by sections of the accumulator

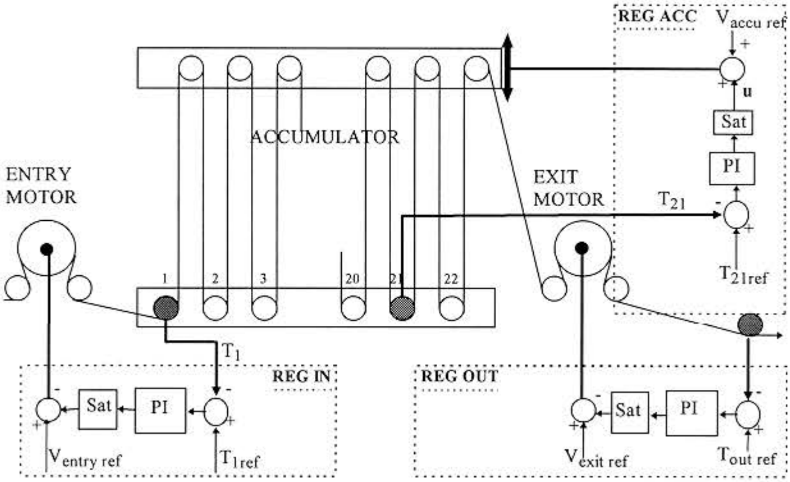


Fig 7 - Existing industrial regulation of the accumulator

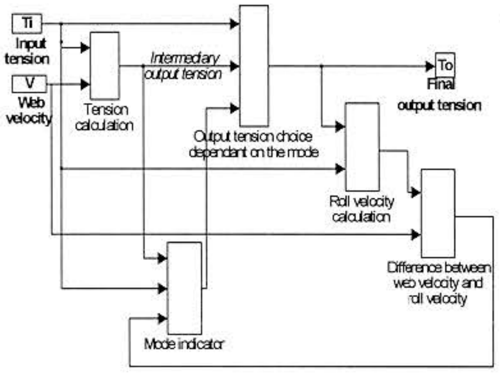


Fig 4 - Principle of tension calculation

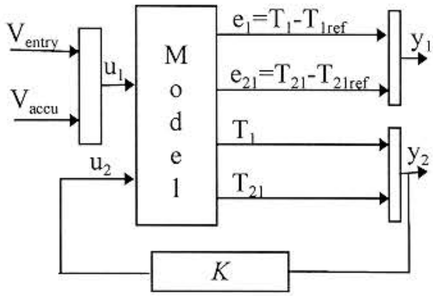


Fig 9 - H_∞ control synthesis

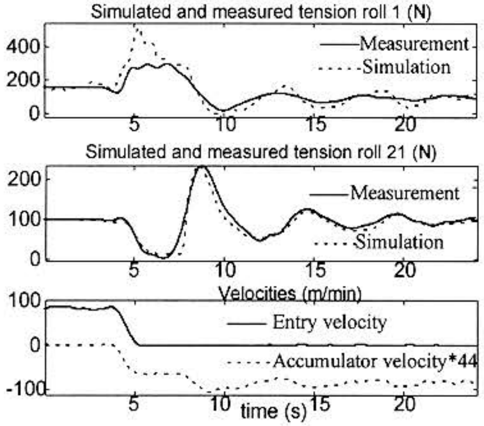


Fig 5 - Simulated and measured web tensions

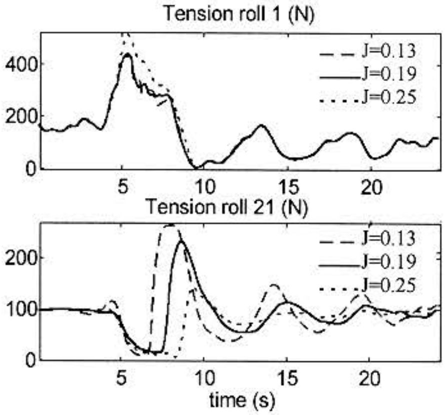


Fig 6 - Roll inertia effect on web tension

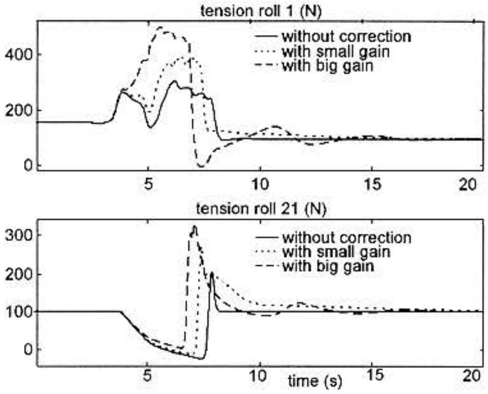


Fig 8 - PI correction effects

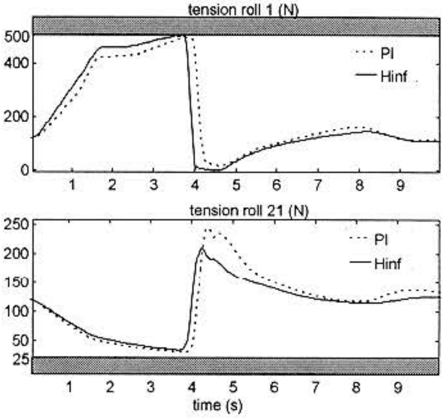


Fig 10-H_∞ and PI controllers comparison

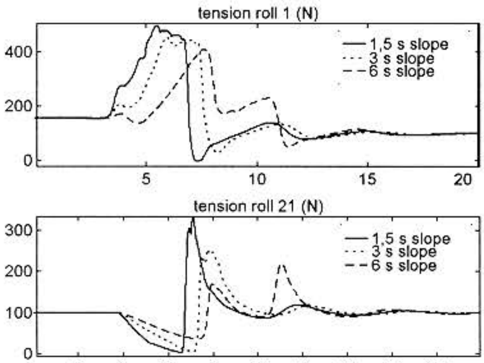


Fig 11 - Tension for different descents

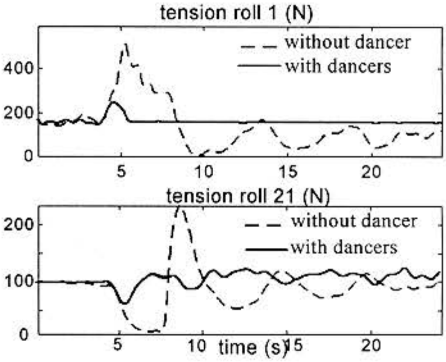


Fig 12 - Dancing roll effect
on web tension

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Web Tension control in an Industrial Accumulator
6/8/99 Session 3 1:15 - 1:40 p.m.

Question:
You didn't mention of I didn't hear what was the material you used.

Answer – H. Koc, Strasbourg University
Polymers

Question – Brian Boulter, Rockwell Automation
If you put a dancer in an accumulator how do you regulate the dancer position?

Answer - H. Koc, Strasbourg University
I just tried a simple controller to regulate the position and I had a maximum variation of the position about 1 meter.

Question – Brian Boulter, Rockwell Automation
So you have no position regulator? You just have constant load and allow it to move freely? What keeps it from slamming into a limit? If you build it like that I can guarantee you that it is going to drift into a limit.

Answer – H. Koc, Strasbourg University
My simulation didn't.

Question – Dan Carlson, 3M
For your infinity controller this is external regulated with the same velocity loops or what are the formats? Describe what the variables are that you are controlling?

Answer – H. Koc, Strasbourg University
The controller is synthesized to have a constant tension during the velocity variations.

Question:
What is the output of the controller? The operating signal of the controller?

Answer – H. Koc, Strasbourg University
It's the torque.

Question – Pagilla Prabakar, Oklahoma State University
What are you minimizing, what is the minimizing performance index for infinity control? What kinds of function are you minimizing?

Answer – H. Koc, Strasbourg University
You have several transfer functions. You minimize the maximum of the Bode diagram of the transfer functions.

Question:
Of what variable?

Answer – H. Koc, Strasbourg University
This is a recent control robust. I can suggest a few books on multivariable control.

Question:
You said measured. Is that experimental results or just computer simulations?

Answer - H. Koc, Strasbourg University
Simulation.

Question:
Even the previous one?

Answer – H. Koc, Strasbourg University
No, the accumulator I have some simulations, some measurements. With the dancing rolls, it was the simulator. The company didn't build this control. I didn't dare to try to control it.

Question:
You have an entry motor, exit motor and you are controlling that accumulator carriage. Do each of these control systems talk to each other? Or are they decoupled?

Answer – H. Koc, Strasbourg University
They are decoupled.