Open access • Proceedings Article • DOI:10.1109/.2001.980997

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Published on: 04 Dec 2001 - Conference on Decision and Control

Topics: Active disturbance rejection control

Active Disturbance Rejection Control for Web Tension Regulation

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Abstract: A new control method is proposed for tension regulation in a web transport system. It is based on a unique active disturbance rejection control (ADRC) strategy, which actively compensates for dynamic changes in the system, and unpredictable external disturbances. A simulation of an industrial application is used to provide realism. The results show the effectiveness of the proposed tension controller in coping with large dynamic variations commonly seen in web tension applications. The remarkable disturbance rejection capability of an ADRC is also demonstrated.

I. Introduction

Tension controls are widely used in web transport and strip processing systems. These systems either feed material from an existing primary processed roll/coil of material into a process for secondary processing, or wind processed material for storage or final shipment. The main purpose of web tension regulation is to maintain the physical integrity of the material that is being processed.

The tension control problem in strip/web processing applications is a complex one because the system dynamics are a function of many process variables that often vary over a wide range. For example, in rolling mills, these variations include changes in roll diameter, product density, web/strip modulus of elasticity, web/strip cross sectional area, the inner speed loop bandwidth and process line-speed. Due to their difficulty and importance in industry, tension problems have drawn the attention of many researchers. One problem is the establishment of a proper mathematical model. Campbell [1] and Brandenburg [2] studied the longitudinal dynamics of a moving web. Campbell developed a mathematical model of a web span but did not consider the tension in the entering span, therefore his model does not predict "tension transfer". This problem was addressed by Brandenburg and Shelton [3], with the assumption that the strain in the web is very small. Brandenburg's work took into consideration the effects of small changes in area that result from strain changes, temperature changes, and register errors.

There are two common approaches used in web processing industries for tension control: open-draw control and closed-loop control. In the "draw control" scheme, tension in a web span is controlled in an open-loop fashion by controlling the velocities of the rollers at either end of the web span. W. Wolfermann and D. Schroder [4,5] used an optimal output feedback method to control the speed of the driven rollers. A decentralized observer was designed to decouple the drives from the web tension acting on the driven rollers and this information is used to improve the speed control of the driven rollers. This method leads to considerable improvement in the speed responses of the driven rollers. An inherent drawback of indirectly controlling tension through speed control is its dependency on the open loop relationship between the speed and tension. This control method cannot reject disturbance due to "tension transfer" from adjacent web spans and interaction between adjacent web spans through an intermediate driven roller. Note that tension is also affected by the change in temperature, material, thickness, as well as other operating variables. It is also very sensitive to noise in the speed feedback devices.

Proportional-integral-derivative (PID) control approach is the primary feedback control law used in industry. For tension feedback control, however, because of the significant variations in system dynamics, PID alone has been shown to be inadequate. K. Reid, K. Shin and K. Lin [6-8] proposed the fixed-gain and variable-gain PID control of web tension in the winding section. For variable gain PID, the control parameters are continuously updated based on the diameter of the roller, which is a major contributor to the system dynamics. This method uses pole placement techniques.

In this paper, we proposed a new methodology for web tension regulation. It is based upon a unique active disturbance rejection control (ADRC) concept. In this approach the disturbances are estimated using an extended state observer (ESO) and compensated during each sampling period. This method was developed by J. Han [9]. A survey paper of this and similar results is available upon request [10]. The proposed ADRC control system consists of the ESO and a nonlinear PD controller. It is designed without an explicit mathematical model of the plant. The controller is designed to be inherently robust against plant variations. Once it is set up for a class of problems within a predetermined range of variation in system variables, no tuning is needed for start up, or to compensate for changes in the system dynamics and disturbance. This method, because of its robustness and disturbance rejection capabilities, is particularly suitable for web tension regulation applications.

In Section II, the web tension problem is introduced. Details of the ADRC control approach is given in Section III. Simulation results based on a simplified linear model and an industrial strip processing application are given in Section IV. Finally, concluding remarks are included in Section V.

II. The Web Tension Regulation Problem

A web refers to any material of a continuous flexible strip which is either endless or very long compared to its width, and very wide compared to its thickness. The web must pass through several processing sections in the manufacturing process of an intermediate or final product. All sections of the continuous process are coupled by the web. Different web tension magnitudes are typically required in each processing section. Severe tension variations in these sections may lead to degradation of product quality, or even the rupture of the material during processing. This results in significant economic loss and negatively impacts process line productivity. In order to minimize the potential for loss, the need arises to adequately control the tension within a predefined range in a moving web processing section.

This research is motivated by the complexed control problem encountered in a web line testing facility, referred to as the Lab-line and is shown in Figure 1. It was used to evaluate web handling control strategies. A simplified one-line diagram is shown in Figure 2.

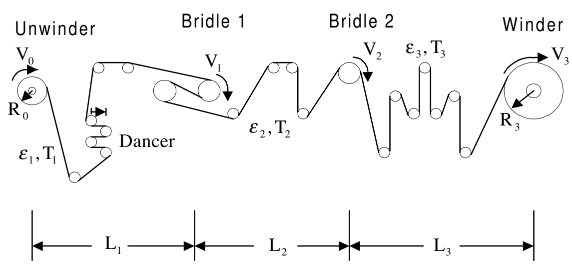

Figure 1. Lab-line illustration

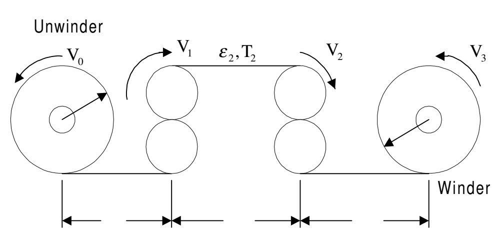

Figure 2. Simplified Lab-line diagram

The tension dynamics associated with the conveyance of a web through a single tension zone is described in (1). It is based upon the principle of conservation of mass in a mass-flow system [11].

$$L_i \frac{dT_i}{dt} = E_i \cdot A_i \cdot (V_i - V_{i-1}) + V_{i-1} \cdot T_{i-1} - V_i \cdot T_i \quad (1)$$

where:

$$V_i = \frac{R_i}{GR_i} \cdot \frac{2\pi}{60} \cdot (\omega_i) \quad (2)$$

The motor/load torque equation is:

$$J_i \frac{d\omega_i}{dt} = \tau_i + \frac{R_i}{GR_i} \cdot (T_{i+1} - T_i) \quad (3)$$

The above equations can be presented in block diagram format as shown in Figure 3. This modular representation includes the hooks that allow coupling multiple sections together. However, it does not include any damping terms. Note that a rigorous representation of equation (1-3) requires the integrators in Figure 3 to be preset to their respective initial conditions [12].

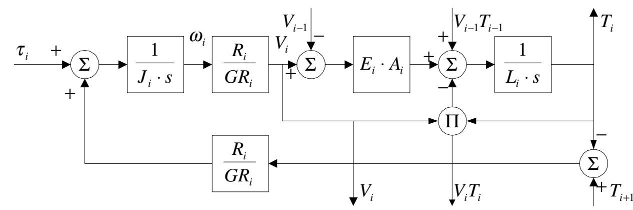

Figure 3 Block Diagram of a Web Tension Zone

For a given operating line velocity LS_i, an approximate linear representation of equations (1-3) can be obtained [11]. A block diagram of the linearized model is shown in Figure 4, with the assumptions that 1) the tension in the web entering the tension zone is zero; 2) the system speed reference V_{i-1} is constant.

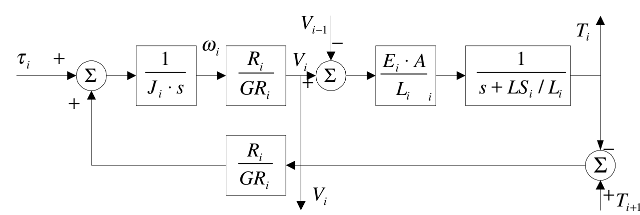

Figure 4 Linearized Block Diagram of a Web Tension Zone

Of particular interest is the behavior of the tension loop at stall (that is when the web stops moving). At this point, with some simplifications, a tension transfer function can be approximated as a typical second order system [22]

$$\frac{T}{\tau} = \frac{k}{\frac{s^2}{\omega^2} + \frac{2 \cdot \zeta}{\omega} s + 1} \quad (4)$$

with $\omega \in [\omega_{\min}, \omega_{\max}]$, $\zeta \in [\zeta_{\min}, \zeta_{\max}]$ and $k \in [k_{\min}, k_{\max}]$. The corresponding differential equation is:

$$\ddot{T} = -2\zeta\omega\dot{T} - \omega^2 T + k\omega^2 \tau \quad (5)$$

Considering the tension coupling, dead zone and other nonlinearities in the system as well as external disturbances, a more generic and realistic differential equation for the tension dynamics is

$$\ddot{y} = f(t, y, \dot{y}, w) + bu \tag{6}$$

where y is tension, u is motor torque, and w is the disturbance. Here, $f(t, y, \dot{y}, w)$ is generally a time-varying nonlinear function that represents the true system dynamics. The difficulty in tension control is mainly due to the fact that the function $f(t, y, \dot{y}, w)$ changes significantly during operation. Thus, better control strategies are needed to solve this practical problem.

III. The Active Disturbance Rejection Controller

The ADRC is based on the idea that in order to formulate a robust control strategy, one should start with the original problem in (6), not its linear approximation in (5). Although the linear model makes it feasible for us to use powerful classical control techniques such as frequency response based analysis and design methods, it also limits our options to linear algorithms and makes us overly dependent on the mathematical model of the plant.

Instead of following the traditional design path of modeling and linearizing $f(t, y, \dot{y}, w)$ and then designing a linear controller, the ADRC approach seeks to actively compensate for the unknown dynamics and disturbances in the time domain. This is achieved by using an extended state observer (ESO) to estimate y, dy/dt, and $f(t, y, \dot{y}, w)$ iteratively. Once $f(t, y, \dot{y}, w)$ is estimated, the control signal is then used to actively compensate for its effect and reduce (6) to a double integration, which in turn becomes a relatively simple control problem. More details of this novel control concept and associated algorithms can be found in [9,10]. A brief introduction is given below.

3.1 The Extended State Observer (ESO)

In order to estimate $f(t, y, \dot{y}, w)$ without knowing its analytical form, the plant in (6) is augmented as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu, \quad x_3(t) \triangleq f(t, x_1, x_2, w) \\ \dot{x}_3 = h(t) \\ y = x_1 \end{cases} \tag{7}$$

where h(t) is the derivative of $f(t, y, \dot{y}, w)$ and is unknown. The reason for increasing the order of the plant is to make $f(t, y, \dot{y}, w)$ a state set such that a state observer can be used to estimate it. One such observer is given as

$$\begin{cases} \dot{z}_1 = z_2 - \beta_{01} fal(z_1 - y(t), \alpha_1, \delta_1) \\ \dot{z}_2 = z_3 - \beta_{02} fal(z_1 - y(t), \alpha_2, \delta_2) + b_0 u \\ \dot{z}_3 = -\beta_{03} fal(z_1 - y(t), \alpha_3, \delta_3) \end{cases} \tag{8}$$

where β_{01},β_{02} and β_{03} are observer gains, b_0 is the normal value of b and *fal(·)* is defined as

$$fal(\varepsilon, \alpha, \delta) = \begin{cases} |\varepsilon|^{\alpha} \, sign(\varepsilon), & |\varepsilon| > \delta \\ \dfrac{\varepsilon}{\delta^{1-\alpha}}, & |\varepsilon| \le \delta \end{cases} \tag{9}$$

This observer is denoted as the extended state observer (ESO) and is the corner stone of the ADRC method.

Remarks:

1. The nonlinear function in (9) is used to make the observer more efficient. It was selected heuristically based on experimental results. Intuitively, it is a nonlinear gain function where small errors correspond to higher gains. This technique is used widely in industrial applications.
2. If α_i *i*=1, 2, 3, are chosen as unity, then (8) is equivalent to the well known Luenburger Observer found in linear system theory;
3. Similar to linear observers, the observer equation (8) reflects our best knowledge of the plant. The information on the range of b in (6) is needed for the selection of b_0 in the ESO. If we know more about the plant, such as the roll diameter, which gives us part of $f(t, y, \dot{y}, w)$, then this information should be incorporated into the observer to make it more efficient.
4. Note that there is a linear segment in (9) in the neighborhood of the origin. It was discovered experimentally that the nonlinear function in (9) makes the observer converge faster than its linear counter part and the linear section in (9) and makes the output of the observer smoother.
5. The proper selection of the gains and functions in (8) are critical to the success of the observer. One way to get started is to design the linear observer first and then gradually increase the nonlinearity to improve the performance. This is particularly helpful for people who experiment with this method for the first time.

3.2 The Control Law

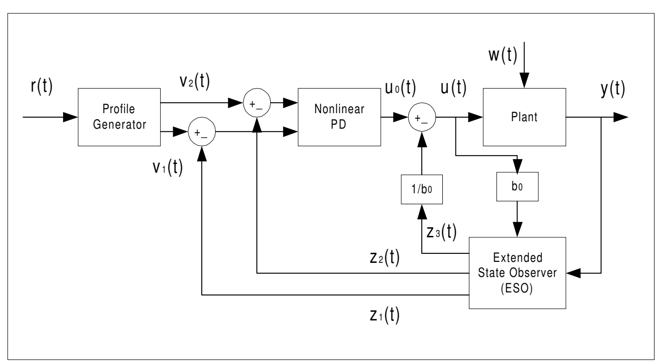

Figure 5. Structure of the ADRC

The architecture of the ADRC is shown in Figure 5. It consists of three components: the Profile Generator which provides the desired transient trajectory for tension to follow from the initial value to the setpoint; the ESO which is described above, and the control law which is defined as

$$u(t) = u_0(t) - z_3(t)/b_0 \qquad (10)$$

This control law reduces the plant to a double integration and is controlled by the nonlinear PD controller:

$$u_0(t) = K_P fal(\varepsilon_P, \alpha_P, \delta_P) + K_D fal(\varepsilon_D, \alpha_D, \delta_D) \qquad (11)$$

For example, in positioning applications, $\varepsilon_P = v_1 - z_1$, $\varepsilon_D = v_2 - z_2$, are "position" and "velocity" error, respectively, k_P and k_D are the gains of the PD controller, and $fal(\cdot)$ is the nonlinear function defined in (9).

Note that the profile generator generates the desired output trajectory, $v_1(t)$, and it's derivative, $v_2(t)$. They are then compared to the filtered output, $z_1(t)$, and its derivative, $z_2(t)$. Clearly, the differentiation of the error is obtained without taking the direct differentiation of the set point or the output. This makes the algorithm much less sensitive to noise in the output and discontinuities in the setpoint r(t).

The critical component here is obviously the ESO. Its parameters need to be tuned properly for the ADRC to work. We find it useful to get a rough linear model from test data of the real system, based on which the ESO parameters and feedback gains are tuned. It was discovered that once the ESO is properly set up, the performance is quite insensitive to the plant variations and disturbances.

IV. Simulation Study

The Matlab/Simulink package from Mathworks was used for the simulation. The simulation is carried out in two stages. The validity of the ADRC is examined in the first stage using the simple linear model in (5). Once the parameters are well tuned and successful results are obtained, the ADRC is then tested on a simulated industrial web-line.

Proof of the concept

The ADRC is first tuned and simulated using the linearized plant in (5) with parameters in the ranges of $\omega \in [3.2,13]$, $\zeta \in [0.2,0.9]$ and $k \in [0.8,1.2]$. A discrete version of (8-11) is used with a sampling rate of 1 kHz. For the sake of simplicity, the Euler's formula is used for the discrete approximation.

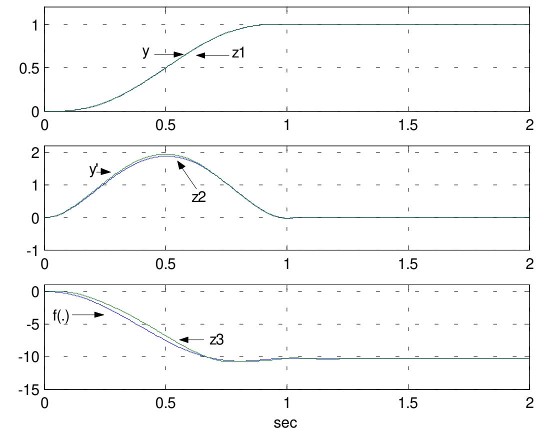

Figure 6 The performance of ESO for simplified model

The ESO output and the plant output are compared in Figure 6. Note that all three outputs of the ESO track their targets quite well. The resulting PD design becomes quite straightforward. The most encouraging part of the simulation is that similar performances are observed for various parameter settings within the range, demonstrating the robustness properties for the controller.

Testing in an industrial setting

Following the successful simulation with the simple model, we then tested the ADRC on a full-scale simulation of the Lab-line shown of Figure 1, which is a four-section process line. The simulation model developed and used by practicing engineers is shown in Figure 7. Note that there are three tension zones but only one tension feedback loop, which is located on the winder side of the process line. The most critical area for tension regulation is at the winder. Note that with the tension loop in place, one may or may not use an inner speed loop on the winder tension regulation scheme. Using the inner speed loop helps to dampen natural frequencies that are lower than the speed loop bandwidth [12]. We elected not to use it for the sake of simplifying the design and also to make the control problem more challenging.

As the web moves through the line, the diameter of the winder roll varies from 3 inches to 24 inches, which roughly corresponds to variations in the linear model of: ω from 3.2 to 13, ζ: from .2 to .9, and k: from .8 to 1.2. Understandably, such changes pose a significant challenge for the controller to be designed for stability, and performance, over the entire operating range.

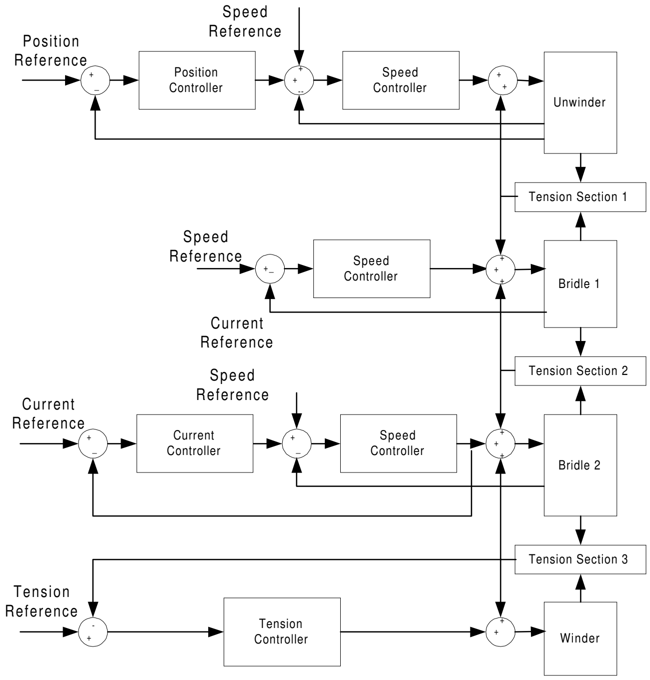

Figure 7 Simulink based industrial simulator diagram

Figure 8 shows the response of web tension loop using the ADRC. The sample period is t_s=10ms, which is consistent with many existing industrial tension application hardware capabilities, such as the Rockwell AutoMax DPS UDC Controller. The parameters are fixed for the ADRC while the tests are conducted at different operating conditions, particularly for different winder diameters. The design specifications call for a 1.5 sec settling time and an overshoot of less than 10%. The ADRC meets both of these transient requirements for all diameter changes. Two extreme cases are shown in Figure 8. A constant 20% rated torque pulse disturbance is also added at t=5 sec to show disturbance rejection properties. Overall, the results are very encouraging.

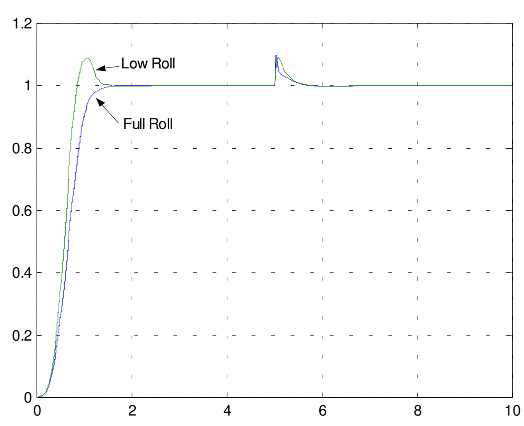

Figure 8. Tension responses at empty and full roll with 20% torque disturbance at t=5sec. (t_s=10ms)

Note that there are NO fixed gain controllers that can come close to this performance. Even the variable gain PID controller used in the industrial application did not perform as well in simulation. No direct comparison is made because we believe it was not optimized and the comparison may not be fair.

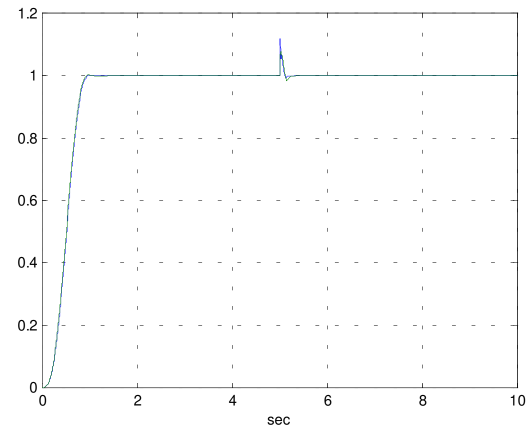

Figure 9 Tension responses at empty and full roll 20% torque disturbance at t=5sec. (t_s=1ms)

It was discovered that ESO's performance is quite dependent on the sampling rate. A faster sample rate of 1 kHz leads to significantly better results than those with sampling rate of 100 Hz. Figure 9 shows the results of the ADRC, using a t_s=1 ms sample period, for the same two extreme operational cases: the empty roll and full roll. There is barely any difference between the two responses. With the analog to digital converter running in the range of a microsecond, a 1-millisecond sampling rate will not be an application problem in the near future.

V. Conclusion

A new web tension control method is proposed. The Active Disturbance Rejection Controller (ADRC) is applied to deal with significant dynamic change in the web transport processes. The new control algorithm in digital form is simulated on a simulation of an industrial process with very encouraging results. We believe that this is a promising new solution for web applications because: 1) it's intuitive; 2) it does not require an explicit mathematical model of the plant under control; 3) it is inherently robust. It was shown that once the ADRC controller is set up properly, it can handle a large range of dynamic changes. High sampling rates result in a great improvement in the ADRC control performance.

Acknowledgement:
The authors would like to express their sincere appreciations to Prof. Jingqing Han and Prof. Yi Huang for their suggestions during the course of the research.

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Appendix I

Nomenclature

J_{motor}	motor inertia [kgm^2]
J_{load}	reflected roll (load) inertia c
J_i	$J_{motor}+J_{load}$ [kgm^2]
V_i	i'th roll surface velocity [m/min]
ω_i	i'th motor rotational velocity [rpm]
R_i	i'th roll radius [m]
GR_i	i'th roll gear ratio
L_i	i'th tension zone length [m]
T_i	i'th tension zone tension [kgf]
τ_i	i'th roll reflected shaft torque [kgf.m]
E	modulus of elasticity [kgf/mm^2]
A	cross sectional area [mm^2]
LS_i	opearting line speed [m/min]
$S_i = LS_i \cdot GR_i$	i'th motor gear-in speed [rpm]