EFFECTS OF PID GAINS FOR CONTROLLER WITH DANCER MECHANISM ON WEB TENSION

by

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ABSTRACT

A dancer mechanism is widely used in connection with a tension controller in the tension control systems for web printing presses. The common tension controllers perform proportional, integral, and/or derivative (PID) control. This paper investigates the effects of PID gains on the web tension under various operating conditions, such as variations of paper roll size, various desired web tension levels, various web speeds, and other parameters. A mathematical model representing the unwind and the infeed sections of a printing press is used to simulate web tension in connection with various controllers and operating conditions. Effects of the individual gain in various controllers using proportional (P) control, proportional-derivative (PD) control, proportional-integral (PI) control, and PID control are discussed and compared.

NOMENCLATURE

d	Paper density
E	Modulus of elasticity of paper
F_1	Geometry function of the dancer design
F_2	Geometry function of reel roll design
h	Paper thickness
J	Polar moment of inertia of reel roll
J_b	Polar moment of inertia of rotating elements of electric brake
J_d	Polar moment of inertia of dancer arm
J_s	Polar moment of inertia of reel roll shaft
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gains
L	Span of the infeed section
L_1	Span of the unwind section
$L_{1,i}$	Initial span of the unwind section
M	paper roll mass
p	Dancer air load
R	Paper roll radius
R_c	Paper roll core shaft radius
R_i	Initial paper roll radius
Q	Paper roll driving torque

Q_b	Brake torque
Q_f	Friction torque
Q_i	Nominal brake torque setting
Q_p	Pulling torque
S	Paper longitudinal strain under tension
T_1	Web tension, unwind section
T_2	Web tension, infeed section
V	Speed of web entering the printing unit
V_1	Speed of web leaving the unwind
W	Web width
X(1)	Reel roll angular velocity
X(2)	Dancer arm position
X(3)	Dancer arm angular velocity
X(4)	Web free length entering the unwind
X(5)	Web free length leaving the unwind
ϵ	paper elongation rate
τ	time

1. INTRODUCTION

1.1. PID Web Tension Controller

Tension variations in web printing presses affect the printing quality and tend to cause web break, wrinkles and other problems. One of the key design criteria for the web press tension control system is to maintain the tension within a narrow range as the web entering the first printing unit.

The majority of web press tension control systems use a dancer mechanism as feedback element[1]. In stead of the error signal representing the difference between desired tension and actual tension, the response of the controller is driven by the dancer movement (see Section 1.2). Proportional-integral-derivative (PID) controllers have been widely used in the tension control systems due to its operational simplicity and economy[2]. Fixed gains applications met basic requirements during the years when the demand of web press performances was not critical. However, competition, capital resources, and marketing evolution have caused printers and publishers to demand web presses that can produce not just high quality print products, also under a wider range of operating conditions. As a consequence, the web tension control system needs to be able to control the tension under a wide range of dynamic conditions such as speed changes, variations in paper roll sizes (width and radius), and paper property. A general understanding among the industries is that variable gains applications should improve the control systems' capabilities, and therefore expand their operating ranges.

Most equipment manufacturers or system suppliers have accommodated variable gains applications that require manually tuning the gains. Properly tuning the gains as the operating conditions vary constantly has been a challenge task for system designers and users. Many studies on using and tuning the PID gains have been reported[3]. Reid and Shin [4] showed the improvement of a system's step response by using the optimal gains as the paper roll size varied. Others presented methods of tuning the variable gains based on the system dynamic responses. For press manufacturers and printers the concept that relates gain settings and the output tension is more beneficial. In our study we investigated how PID gains affected the web tension at various operating conditions, namely paper roll size, speed, and etc. The study was conducted by using a model that was derived from an existing product and was able to simulate real time web tension responses to various operating conditions.

1.2. System Description

The paper adopts an existing product as a design example of web tension control system. The design, as depicted in Figure 1, contains two sections: unwind and infeed. The unwind section includes a reel stand and a dancer mechanism. The reel stand supports the paper roll shaft and an electrical brake attached at one end of the shaft. The key components of the dancer mechanism are a spring or air cylinder restrained dancer arm and a position sensor. The dancer arm is pivoted to a pin that is aligned with the position sensor to signal the dancer arm's swinging. The infeed section contains a driven roller called drum, a nip roller, and an adjustable differential gear box. The differential gear box causes the drum speed to lag behind the press speed a small amount. The nip roller prevents the web from slipping on the drum surface as the drum pulling the web from the unwind section.

Figure 2 shows the control block diagram. The dancer mechanism serves as the feedback element for the unwind in the sense that its movement is determined by the difference between the desired tension and the actual tension. The position sensor provides the information of the dancer arm's movement to the PID controller. The controller determines the brake power out of the electrical brake. The brake generates a brake torque on the paper roll shaft. The web feedrate is driven by the paper roll pulling torque generated by the unwind tension, and is counterbalanced by the brake torque and friction torque.

The system requires the user to set the desired tension level for the unwind and the infeed. For the tension at the unwind, the user adjusts the spring rate or the air pressure of the air cylinder that restrains the dancer arm. The infeed tension is set by adjusting the differential gear box ratio, which determines the drum speed relative to the press speed.

1.3. Control Objectives

The ultimate objective is to maintain the tension fluctuation within 1.5% of the desired tension level at constant press speeds as the web passes over the drum. The paper roll radius decreases as the web is running at a speed, and so is the paper roll inertia. The changing rates of the paper roll radius and inertia at a constant speed depends on instantaneous roll size. Another key objective is to maintain the fluctuation within 3% during the speed changes. The change of the speed add another dimension to the changing rate of the roll size.

Other secondary objectives include the stability of the dancer movement and web break prevention. Since these objectives are not directly relate to PID controller, they are not discussed here.

2. DYNAMIC MODEL OF TENSION CONTROL SYSTEM

2.1 Dynamic Model

The following is the model for the control system depicted in Figure 1 and 2. The equations that represent details of physical and geometrical dimensions are off the main subject, and are not shown here. The model is developed based on the following assumptions for clarity:

- The web is of perfectly elastic material.
- The friction between web and roller is not considered.
- The web thickness is small relative to the roll size.
- The dynamics of the position sensor and transmission components are considered negligible.

The equations for the paper roll radius and mass, and reel roll polar moment of inertia are:

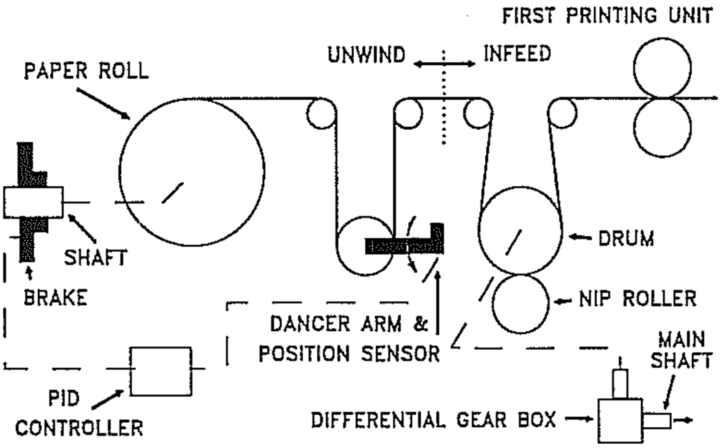

Figure 1: System diagram of the unwind and infeed for web presses.

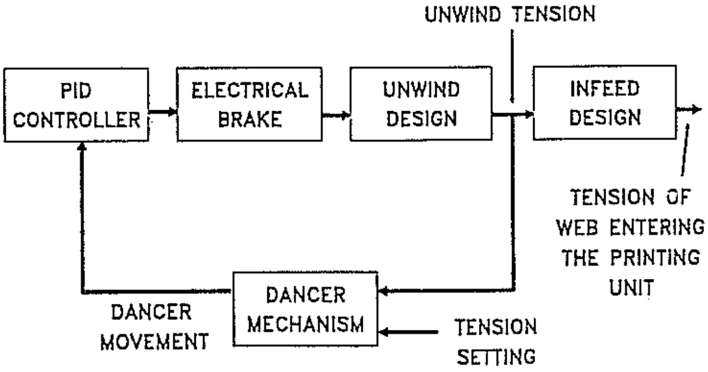

Figure 2: Control block diagram.

$$R=R_i-\frac{h*X(1)}{2*\pi} \qquad (1)$$

$$M=d*W*R^2*\pi \qquad (2)$$

$$J=\frac{M*R^2}{2}+J_b+J_s \qquad (3)$$

The brake torque is determined by the dancer arm's movement and the PID gains as follows.

$$Q_b=Q_i+K_p*X(2)+K_d*\frac{dX(2)}{d\tau}+K_i*\int X(2)\,d\tau \qquad (4)$$

The torque that rotates the reel roll is the subtraction of the brake torque and friction torque from the pulling torque caused by the unwind tension, i.e.,

$$\begin{aligned} Q &= Q_p - Q_b - Q_f \\ &= T_1 * W * R - Q_i - Q_f - K_p * X(2) - K_d * \frac{dX(2)}{d\tau} - K_i \int x(2) * d\tau \end{aligned} \tag{5}$$

The reel roll angular acceleration is

$$\frac{dX(1)}{d\tau} = \frac{Q}{J} = \frac{Q_p - Q_f - Q_b}{J} \tag{6}$$

and the speed of the web entering the unwind is

$$\frac{dX(4)}{d\tau} = R * X(1), \tag{7}$$

therefore the web speed leaving the unwind and entering the infeed is

$$\frac{dX(5)}{d\tau} = \frac{V_1}{1+S} \tag{8}$$

The dancer arm angular position is X(2), its angular velocity is

$$X(3) = \frac{dX(2)}{d\tau} \tag{9}$$

and the angular acceleration is

$$\frac{dX(3)}{d\tau} = \frac{T_1 * W * F_1(X(2), p)}{J_d} \tag{10}$$

The span of the unwind section varies with the paper roll radius and the dancer position:

$$L_1 = L_{1i} + F_2(R) + F_1(X(2), p) \tag{11}$$

therefore the web elongation in the unwind section is

$$S_1 = \frac{L_1 - (X(4) - X(5))}{X(4) - X(5)} \tag{12}$$

and the web tension in the unwind section is

$$T_1 = S * E \tag{13}$$

The tension of the web leaving the infeed and entering the printing unit is expressed as [5]:

$$\frac{dT_2}{d\tau} = \left(\frac{V}{1+T_2*\epsilon} - \frac{V_1}{1+T_1*\epsilon}\right) * \frac{(1+T_2*\epsilon)^2 * E}{L_2} \tag{14}$$

2.2 Operating Range

A computer program that performs numerical integrations of dynamic model was employed to solve the above equations and to simulate the real time tension responses. The input data of the program, representing the press operating conditions, are paper roll size, press speed, rate of speed change, desired tension, and the controller settings. The press was designed for a range of operating conditions as listed in Table 1.

Condition	Range
paper roll radius	<= 25"
paper roll width	<= 46"
speed	200-1500 fpm
rate of speed change	4-8 in/sec^2
desired tension	1-5 pli

Table 1: Operating Range

3. SIMULATION RESULTS FOR VARIOUS CONTROLLERS

To investigate how the gains affect the web tension, four types of control are used in the dynamic model (Section 2.1, Equation 4): P, PD, PI, and PID control. The investigation was carried out by using the simulation program. The simulations covered the entire operating range listed in Table 1 for each type of control, in which a wide range of gains were used. Notice that the values of the gains depend more on the modeling scale than on the physical scale of the web transport system. Therefore their absolute values are not as meaningful as their relative values to each others for the purpose of our discussion. We have chosen a scale factor so that a typical proportional gain is in the range from 5000 to 50000.

The investigation results are summarized as follows. The following data show the simulations for a 36-inch wide paper roll, in which the desired web tensions of the unwind and the infeed are set respectively at 2 and 4 pounds per inch of width (pli). Other design and input parameters can be found in Appendix.

3.1. Effect of K_p for P Controller

3.1.1. The Effect of K_p on Tension

When using only proportional control, the brake torque varies strictly with the dancer position. A good K_p for a paper roll is to keep the tension within the control objective and cause little oscillation through the entire range of roll radius. If K_p deviates from a suitable range, higher or lower, the web tension level drops out of the desired range. Figure 3 shows how web tension varies as the roll radius becomes smaller for a given K_p under a typical set of conditions. As shown in Figure 3, the smaller the roll is, the more the tension level drops. Further deviations from desired K_p cause the control system unstable.

3.1.2. K_p versus Roll Radius

Figure 4 shows the ranges of K_p which maintain the tension satisfactorily dwindle as the time goes by and the roll radius decreases. The range of K_p that keeps the tension variation within the control objective is large for a large roll. This range is narrower as the roll becomes smaller as shown in Figure 4.

3.1.3. The Effect of K_p on Tension Oscillation

As shown in Figure 5, when high enough K_p (within the desired range as shown in Figure 4) for a radius R is not possible, lower values of K_p not only reduces the tension level, also tend to increase the oscillation. Figure 6 shows a similar trend during a speed change. For a specific K_p, however, the oscillations are larger as R become smaller.

3.2. Effects of K_p and K_d for PD Controller

Figure 7 shows a small value of K_d reduces tension oscillation during a constant speed for a specific K_p. Figure 8 shows that K_d reduces oscillation due to other disturbances such as a speed change. PD control has no effect on tension level when roll radius is large, and has little effect when roll radius is small.

3.3. Effects of K_p and K_i in PI Controllers

For a given K_p which would not cause the system to be unstable, adding a integral control not only increases the tension level towards desired level, but also increases the oscillation. As shown in Figure 9, a higher K_i tends to increase the oscillation more as shown in Figure 9. Figure 10 shows that the oscillations are severer for smaller radius for the same K_p and K_i. If K_i is too large, it will make the system to become unstable.

3.4. Effects of K_p, K_i, and K_d for PID Control

Figure 12 shows a satisfactory performance in using a P controller requires K_p several times as large as the K_p for a PID controller as indicated in Figure 11. Generally values of K_i and K_d need not to be as large as K_p.

4. DISCUSSION

The above simulation results are based on a product whose design is quite typical in the printing industry[6]. The data for physical model and operating parameters are from existing design except the values of gains. In theory a proportional controller alone is able to provide a satisfactory performance if the control system performance characteristics conform with those shown in Figure 4. Then a K_p is chosen so that it is in the desired K_p range for the entire range of R as shown in Figure 12. In reality such choice is not always possible due to design limitations which involve dancer mechanism, controller, and electric brake capabilities. In most cases the maximum K_p allowed by the design is out of the desired K_p range for smaller R as shown in Figure 12.

A PD controller is mostly useful to reduce tension oscillation, but is hardly useful to improve the tension level for smaller R when K_p is not high enough (shown in Figure 3). For a PI controller, while K_i compensates for the tension level due to a smaller K_p, it increases the tension oscillation that may cause an undesirable result. When a K_p suitable for the entire range of operating conditions is not possible to obtain, a PID controller would offer a great possibility to achieve the control objective.

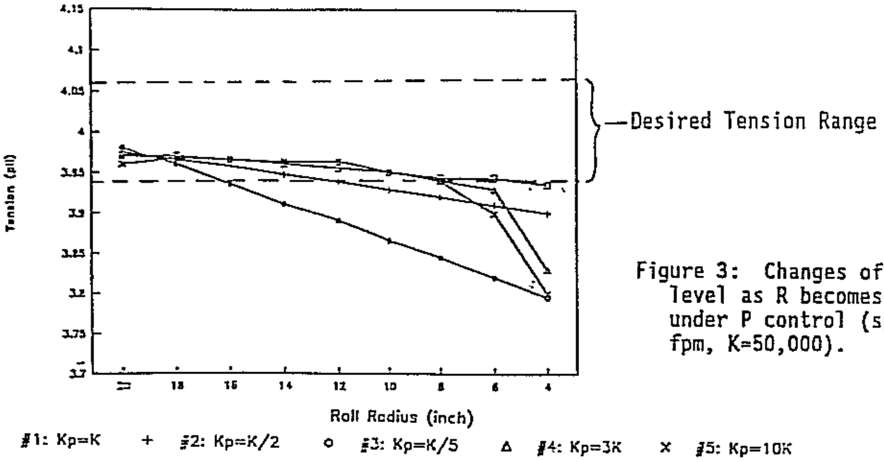

Figure 3: Changes of tension level as R becomes smaller under P control (speed=1200 fpm, K=50,000).

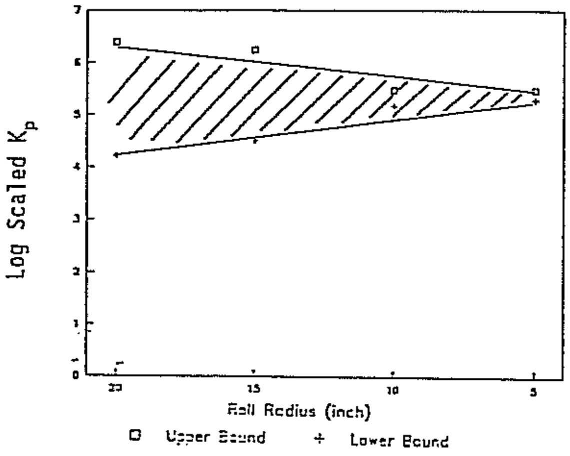

Figure 4: Ranges of K_p that maintain the tension within the control objective are narrower as R is smaller (speed=1200 fpm).

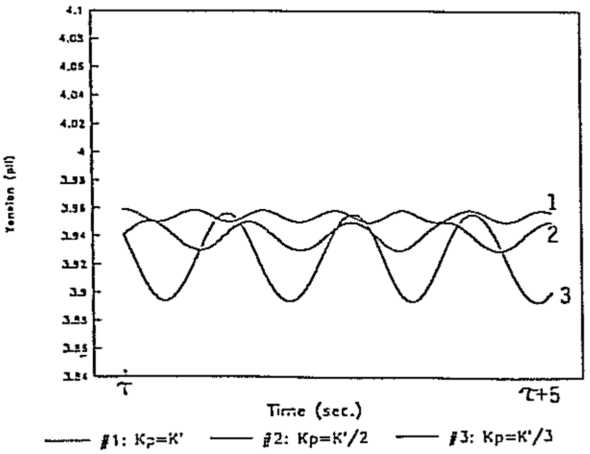

Figure 5: Using lower K_p in a P controller tends to lower the tension level and increases the oscillation for a given R and speed. (Figure is for R=15", speed=1200 fpm, K'=30,000.)

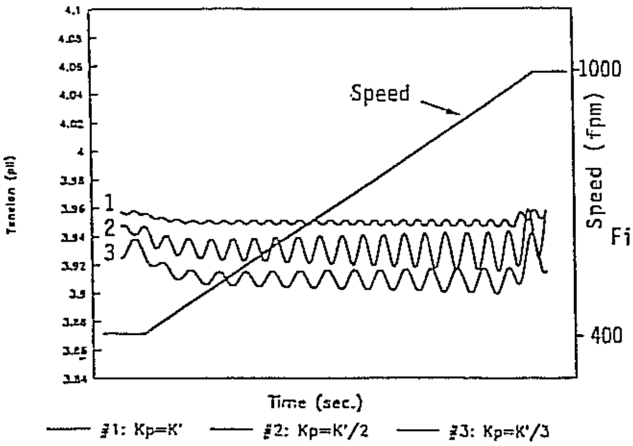

Figure 6: Comparing the same values of K_p's as in Figure 5 during a speed change. (Figure is for a R=15" and acceleration=6"/sec^2.)

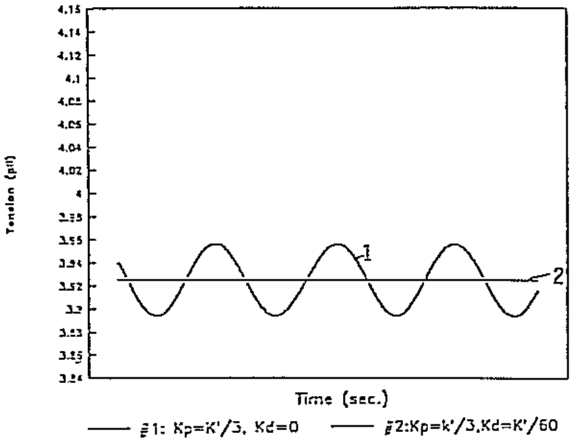

Figure 7: Oscillation can be reduced significantly by using a PD controller with K_d being a small fraction of K_p (K'=30,000).

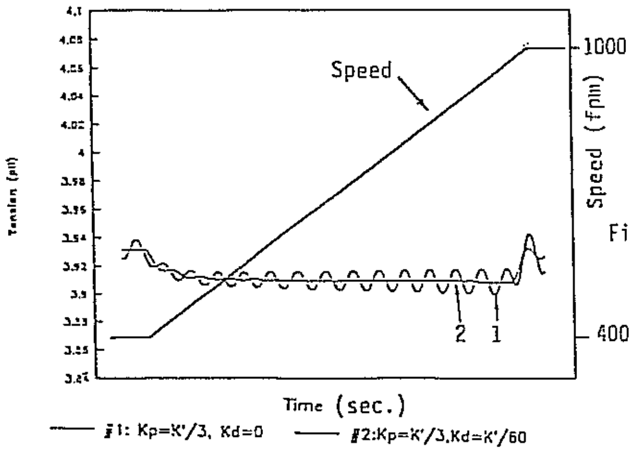

Figure 8: K_d can reduce oscillations caused by a speed change (R=15", acceleration =6"/sec^2, K'=30,000).

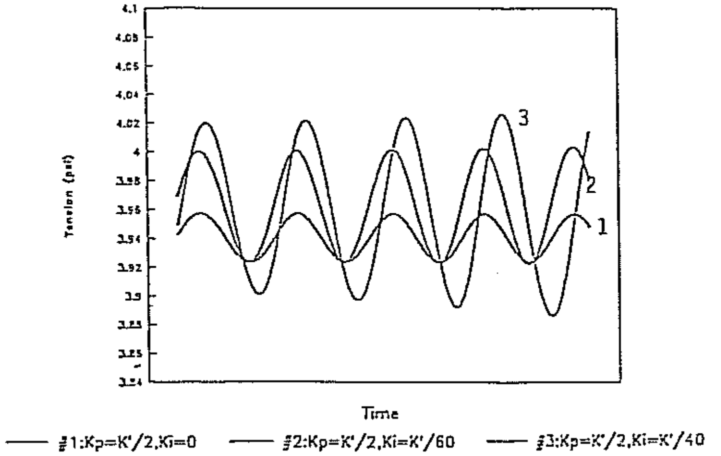

Figure 9: A small amount of K_i increases oscillation and the average tension level (R=15" and speed=1200 fpm, K'=30,000).

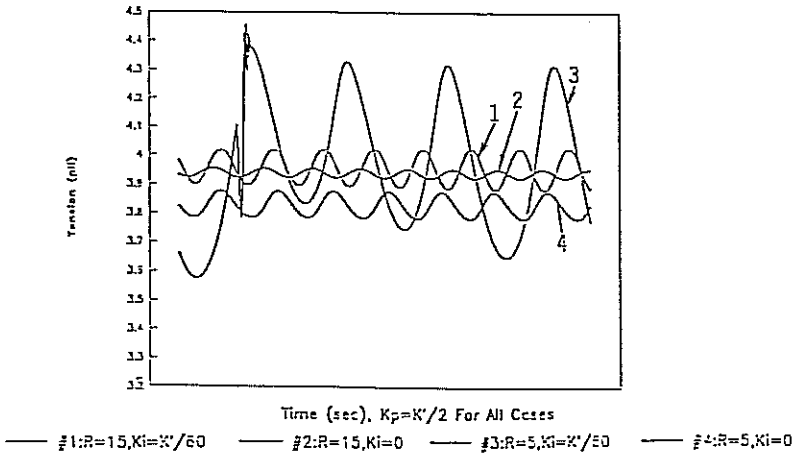

Figure 10: Effect of K_i for R=15" and 5" (speed=1200 fpm, K'=30,000).

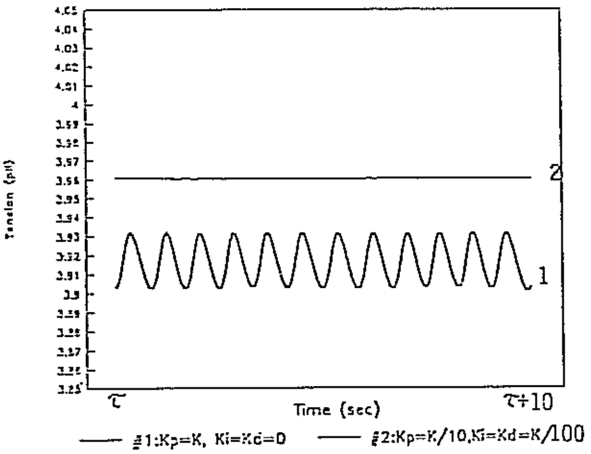

Figure 11: A satisfactory performance can be achieved by using a PID controller with relatively smaller values of K_p, K_i, and K_d, respectively. (For R=5", speed=1200 fpm, K=50,000.)

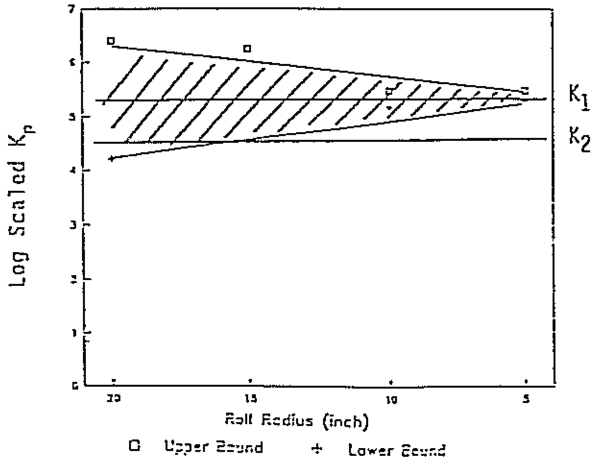

Figure 12: A proportional control provides satisfactory performance for the entire range of R if K_p=K_1 is possible. If K_p=K_2, the tension level drops when R is smaller.

The measures used to compensate for insufficient gains were not the interest of the subject, and therefore were not covered. Simulations with other roll sizes also showed similar results which are not reported here. While the effects of the gains and their trends shown in Section 3 are not guaranteed to be conclusive, the simulation results were all conformed to each other within the range of the operating conditions listed in Table 1, which is also part of the press design specifications.

5. CONCLUDING REMARKS

In this paper we have investigated the effects of PID gains on the web tension under various operating conditions, including variations of paper roll size, various desired web tension levels, various web speeds, and other parameters. A mathematical model representing the unwind and the infeed sections of a printing press was used to simulate web tension in connection with various controllers and operating conditions.

We also compared the effects of the individual gain in various controllers using P control, PD control, PI control, and PID control.

Understanding the effects of the gains on the web tension is as important as determining the optimal gains for various conditions. Our future study will focus on developing a methodology for tuning the optimal gains.

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APPENDIX

A. Paper physical Data

d= .0000775 lb-sec^2/in^4
E= 2000 lb/in
h= .004 in

B. Design Parameters

J_b= 63.638 lb-in-sec^2
J_d= 2.393 lb-in-sec^2
J_s= 3.11 lb-in-sec^2
L= 103.115 in
L_1= 120.571 in
p= 6.472 lb/in of web width
Q_i= 1300 lb-in