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The Effect of Employing an Optimal Web Velocity Profile on Transverse Vibrations in Roll-to-Roll Manufacturing

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The quality of web products is significantly affected by the running velocity of a process line, especially during the stages of start up and shutting down of a web processing line. At these stages, a remarkable transverse variation (web flutter) are observed due to employing improper input velocity. Web flutter may cause some web defects such as wrinkles, poor printing and even web breakage. Therefore, employing an optimal web velocity profile is crucial to minimize web transverse vibrations during the transport of web through different processing sections in a web process line. In this paper, an optimal velocity profile along with common velocity profiles (widely used in industry) have been utilized in a running web line to demonstrate the effect of web transport velocity on transverse vibrations. Comparative experimental results are presented and discussed.

Keywords: Optimal Web Velocity, Transverse Vibration, Web Flutter, Roll-to-Roll Manufacturing

1 Introduction

Web handling processing pervades many engineering applications in industry today. It provides high productivity and better performance over conventional manufacturing. Examples of web products are thin plastics, composites, textiles and paper. Web handling involves unwinding web material, then feeding it to a line process section and finally, winding it back into a roll. In a web handling process line, the web is moving throughout different process sections such as printing, coating, heating, cooling and drying. It is essential that the web is running in a specific velocity and tension in the longitudinal direction to achieve good quality products. Deviation from velocity and tension input references may cause inferior web products. Some of the problems, that are encountered in web handling industry, are introduced in Refs. [1-7]. It is crucial to employ an optimal velocity profile in a web line process to attenuate transverse vibrations generated due to disturbances encountered during manufacturing processes.

Web transport velocity has a major impact on the quality of finished web products. A remarkable transverse vibrations are observed during deceleration or acceleration of a web process line due to improper velocity trajectory implementation at these processes. These vibrations act as disturbances to web handling processing line. Vibration problems have been investigated by many researchers [8-16]. Shin et al. [17] studied the effect of translating speed on the vibration of an axially moving web. The study showed that the transport velocity has a significant effect on web vibrations. The dynamical behavior of axially transporting webs is significantly affected by the running velocity of a web processing line [18]. Nguyen and Hong [9] studied transverse vibration for an axially transporting membrane encompassed by two fixed rolls. Suppression of transverse vibrations was achieved by employing an optimal control algorithm. The proposed method was employed to regulate transport velocity. Web flutter of an axially transporting viscoelastic web was suppressed by utilizing an optimal velocity profile [12]. The proposed approach in Ref. [12], will be employed in this paper and compared with other velocity profiles that are commonly used in industry applications. The rest of this paper is organized as follows. Section 2 presents the theoretical concept to design the optimal velocity profile. A systematic experimental procedure to implement velocity profiles on a web handling process is introduced in Section 3. Section 4 presents analyzing and discussing experimental results. Conclusions are introduced in Section 5.

2 Optimal Velocity Design

The governing equations of in-plane (Eq. 1) and out-of-plane (Eq. 2) motion of an axially viscoelastic moving web are presented in Ref.[12]:

$$M^{uv}\ddot{q}^{uv} + C^{uv}\dot{q}^{uv} + (V^2 H^{uv} + \dot{V}C^{uv} + K^{uv})q^{uv} = F^{uv} \tag{1}$$

$$M^w\ddot{q}^w + 2VC^w\dot{q}^w + [(V^2H^w + \dot{V}C^w + K^w(q^{uv}) + KK^w(\dot{q}^{uv})]q^w = 0 \tag{2}$$

See Ref. [12] for more details about the derivation of the above Equations. The input velocity is denoted by V, which needs to be evaluted to obtain the optimal velocity trajectory. Transverse vibration energy of an axially moving web is defined as:

$$E_w(t) = \frac{1}{2}\int_A \rho h\left(\frac{\partial w}{\partial t} + V\frac{\partial w}{\partial x}\right)^2 dA + \frac{1}{2}\int_A \left[\sigma_x\left(\frac{\partial w}{\partial x}\right)^2 + \sigma_y\left(\frac{\partial w}{\partial y}\right)^2 + 2\sigma_x\sigma_y\left(\frac{\partial w}{\partial x}\frac{\partial w}{\partial y}\right)\right]dA \tag{3}$$

The state-space form of the out-of-plane displacement shown in Eq. 2, can be written as:

$$\dot{X}(t) = A(t)X(t) \tag{4}$$

Where $\mathrm{X}(t) = (((\dot{q}^w(t))^T, (q^w(t))^T)$, and A is defined as: $A(t) = \begin{pmatrix} -2V(M^w)^{-1}C^w & -(M^w)^{-1} Z^w \\ I_{N^2xN^2} & 0_{N^2xN^2} \end{pmatrix}$

Where $Z^w = V^2H^w + \dot{V}C^w + K^w(q^{uv}) + KK^w(\dot{q}^{uv})$

Equation (4) can be rewitten in the following form:

$$\dot{X}(t) = V(t)A_1X(t) + V^2(t)A_2X(t) + \dot{V}(t)A_3X(t) + A_4X(t) = F(X, V, \dot{V}) \tag{5}$$

Therefore, Eq. 3 can be written as [9]:

$$\overline{E}_w(t) = \frac{1}{2}X^T(t)P(t)X(t) \tag{6}$$

The latter equation can be solved to determine the optimal velocity trajectory which results in minimizing the cost function $\overline{E}_w(t)$. The optimal velocity profile (obtained from solving the cost function equation) will be fed into a web handling system and the resulting transverse vibrations will be monitored and recorded. The procedure of implementing the velocity profiles in the web line, is presented in the next section.

3 Experimental Setup

Experiments have been conducted to demonstrate the influence of utilizing different velocity inputs on web transverse vibrations . Figure 1 shows the web handling line platform called the Euclid Web Line (EWL). It is located in the Web Handling Research Center at Oklahoma State University, USA. All experiments were conducted at the EWL, which memics web processing lines widely used in modern industries. The web handling line has four sections: unwind, S-wrap, pull roll, and rewind. Schematic of the web line platform is shown in Fig. 2.

Fig. 1 *Web handling line (EWL) platform*

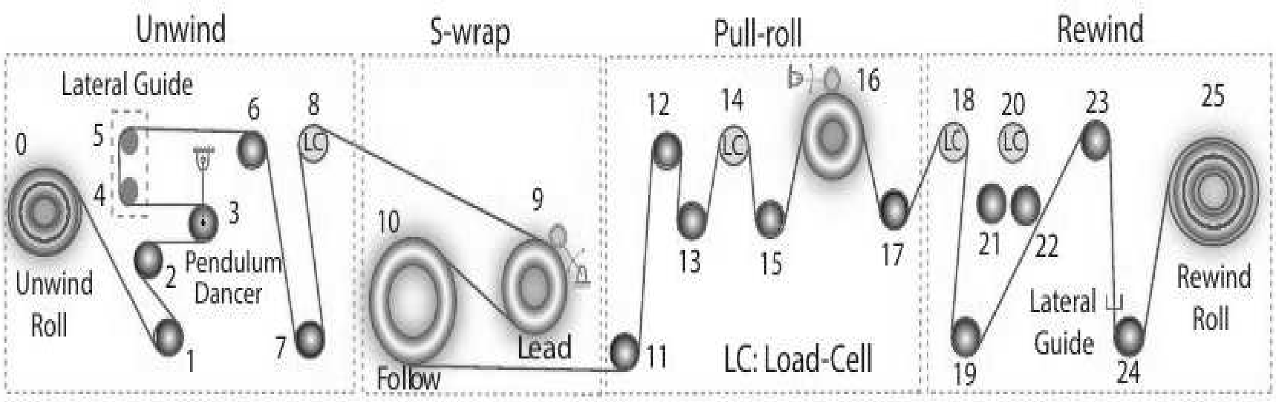

Fig. 2 *Schematic of the web handling platform shown in Fig. 1*

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The pull roll and S-wrap sections are running at a line speed specified by the operator, which is the master speed of the web process line. The speed of unwind and rewind rolls is changing close to the master speed in order to attenuate web tension variations in these sections. RSLogix 5000 is a software (designed by Rockwell Automation), which is utilized to program ControlLogix 5000 controller (advanced Programmable Logic Controller). This controller is the main part of the EWL control system. Hardware configuration and control algorithm implementation are controlled by ACDrive controller. The proposed approach in Ref. [12], (which is obtained by solving the optimal control method) is injected into web handling line through ACDrive controller, along with other conventional velocity profiles used commonly in industry. The AC drive receives the input velocity trajectories from the ACDrive controller, and sends signals to the motor to track the reference velocity trajectory. The velocity profiles were fed into the driven rolls during the process of stoppage (deceleration) of the running web line with a desired time of 4 sec (suppression of transverse vibration energy should be achieved at the given time).

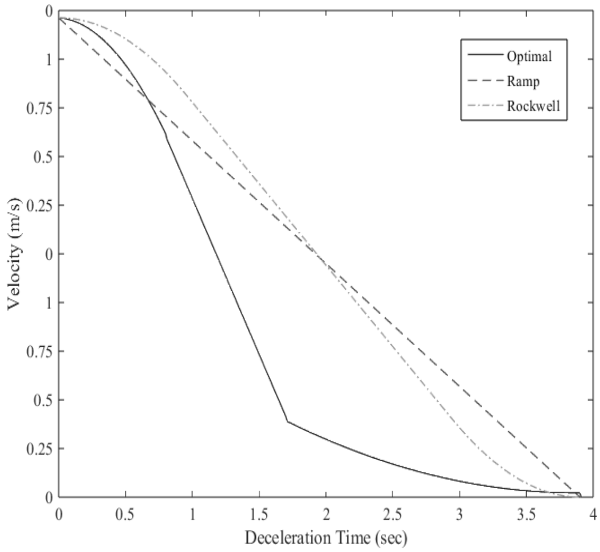

Fig. 3 *Velocity declaration profiles utilized in the web handling line*

Figure 3 shows the utilized velocity deceleration profiles that were employed in the running web handling line, i.e, optimal, ramp and Rockwell velocity deceleration profiles. The optimal velocity trajectory was generated from the optimal control problem explained in Section 2. Constant slope ramp velocity (conventional) deceleration profile is commonly used in industry during the process of shutting down a web processing line. Rockwell or S-curve velocity profile is the built-in velocity deceleration profile in Euclid web line provided by the Rockwell Automation company.

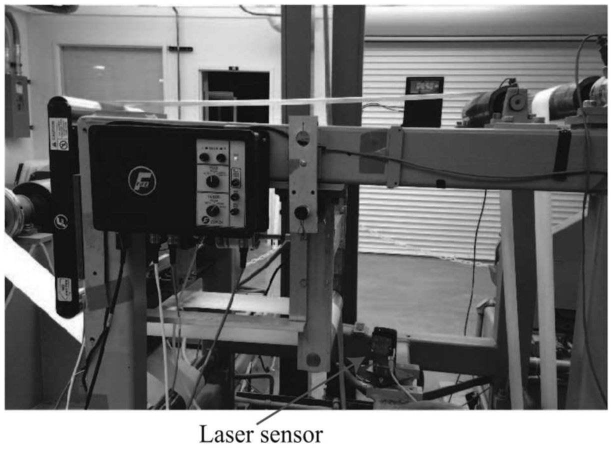

Fig. 4 *Location of the laser sensor used in transverse vibration measurements*

Transverse vibrations of the web material were measured using a laser sensor amounted on the web line. The laser sensor was calibrated to convert the output voltage of the sensor to distance measurements. Figure 4 shows a laser sensor used to measure transverse vibrations. The sensor was installed on the web line in two different web span locations. The sensor was mounted between rollers 5 and 6 and between rollers 19 and 22. These location were chosen because they were close to the unwind and rewind rolls where the transverse vibrations are expected to be significantly observed compared to other locations in the web line. The web material that was running in the web line is called Tyvek. The properties of Tyvek web material are given in Tab. 1.

Tab. 1 *Mechanical properties and dimensions of Tyvek*

Parameter	Value
Young's Modulus	640 (Mpa)
Density	380 (kg/m^3)
Width	152.4 mm
Thickness	0.127 mm

4 Experimental Results

Experiments have been carried out to demonstrate the influence of web transport velocity on transverse vibrations during the deceleration (stoppage) of the web handling line. Three different velocity profiles have been fed into driven rolls of the web handling line. Web is transported with a reference speed of 1 m.s^{-1}. The same running conditions were maintained in each experiment for the different input velocity profiles.

Figure 5 shows transverse vibrations (web flutter) resulting from utilizing three different velocity profile inputs shown in Fig. 3, at a tension load of 44.5 N. It can be noticed that web flutter generated by the proposed approach was regulated compared to other input velocity profiles. However, when implementing the Rockwell deceleration velocity profile, fluctuations in transverse vibration were less than that observed in Ramp velocity profile.

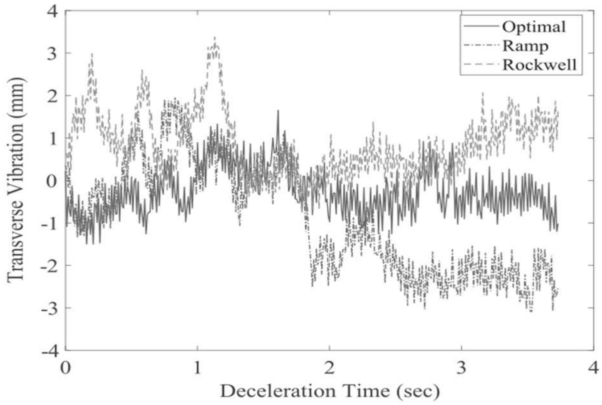

Fig. 5 *Transverse vibrations at different velocity inputs (shown in Fig. 3), at 44.5 N tension load*

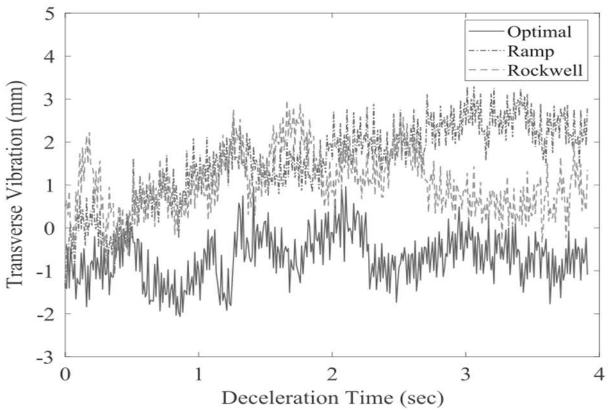

Fig. 6 *Transverse vibrations at different velocity inputs (shown in Fig. 3), at 89 N tension load*

The standard deviation of transverse vibration results corresponding to optimal, Rockwell and ramp input velocity were 0.29, 0.4 and 0.66, respectively. Figure 6 shows transverse vibration response at a tension load of 89 N. A similar trend was observed with increasing tension load. However, the fluctuations in transverse vibration were decreased compared to that observed with a lower tension load. The standard deviation of web flutter results corresponding to optimal, Rockwell and ramp input velocity were 0.27, 0.36 and 0.48, respectively. It is evident that implementing the proposed approach assures attenuation of transverse vibrations compared to other velocity inputs.

5 Conclusions

The increase use of roll-to-roll manufacturing industries has led to many encountered challenges that influence quality of web products. The main concerns in web handling industry is transverse vibrations that are generated due to transporting webs through different processing sections, especially at high speeds. In this paper, an optimal velocity profile (generated based on optimal control theory) along with other common velocity profiles were coducted, in order to investigate the effect of utilizing different velocity profiles on transverse vibrations. The contributions of of this work based on setting up and coducting experiments in the web handling platform can be summed up as follows:

- It has been demostrated that running the web processing line by employing the optimal velocity profile resulted in attenuating transverse vibrations compared to other common velocity profiles used in industry.
- The novelty of employing optimal velocity profile on roll-to-roll machines lies on the fact that there are no equipments or devices needed to attenuate transverse vibrations other than controlling the input velocity (optimal velocity trajecctory) of the web processing line.
- This approach can be easily installed and conducted in a web handling line, especially during acceleration/deceleration of web material where transverse vibrations are significantly observed.

Investigating the influence of an air flow surrounding web line, with presence of heat sources, on web flutter can be achieved by including those effects in the governing equation of out-of-plane motion. Designing and implemnting an optimal velocity profile takes into account these effects can be considered as a part of future studies.

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