ADAPTIVE FEEDFORWARD BASED CONTROL STRATEGY FOR ATTENUATION OF PERIODIC TENSION OSCILLATIONS IN ROLL-TO-ROLL MANUFACTURING

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ABSTRACT

Considering the aforementioned issues, an adaptive feedforward (AFF) algorithm that can work in parallel to an existing feedback control systems is developed for control of web tension and to attenuate periodic oscillations. The essential ingredient of the AFF algorithm is the estimation of amplitude and phase of the periodic oscillations based on which a feedforward compensating control action is generated. The action of the AFF algorithm is such that retuning or redesign of the existing feedback controller is not required. Several different configurations of the AFF for different scenarios in terms of where to apply the feedforward action in the control system are investigated. Extensive experiments are conducted on a large web platform with different scenarios and by transporting two different web materials at various speeds. Results from these experiments are presented and discussed. Experimental results show the effectiveness of the proposed AFF algorithm to attenuate tension oscillations.

NOMENCLATURE

D	Roller diameter [ft]
e	Amount of eccentricity [ft]
e_θ	Angular position regulation error [rad]
f	Fundamental frequency of oscillations [Hz]
g	Gravitational acceleration [ft/s^2]
g_1	Adaptation gain
J	Roller inertia [lb ft^2]
m	Roller mass [lb]
t	Web tension feedback [lbf]
t_r	Web tension reference [lbf]
v	Roller velocity feedback [RPM]
v_r	Roller velocity reference [RPM]
v_{ff}	Velocity feed-forward correction [RPM]
ω	Roller angular velocity [rad/sec]
θ	Roller angular displacement [rad]
τ_{ff}	Torque feed-forward correction [lbf ft]
ρ	Web density [lb/ ft^3]

INTRODUCTION

In many roll-to-roll processes the presence of non-ideal rotating machine elements, such as out-of-round material rolls, eccentric rollers, backlash and compliance in the transmissions is unavoidable. These non-ideal elements generate periodic tension and velocity oscillations around the reference value which can deteriorate the performance of the machine or slow down production. Since the periodic oscillations in a measured tension signal may be due to the cumulative effects of many non-ideal elements, designing an intelligent tension control system to compensate for these oscillations is the most desirable solution. In the industry, the use of Proportional-Integral (PI) controllers to regulate web tension and velocity is fairly standard, however, these type of controllers lack the dynamic sophistication required to attenuate periodic oscillations. For this reason, other control strategies need to be investigated to achieve attenuation of oscillations.

While designing a controller for an industrial application, in addition to the usual stability and performance issues, there are other aspects to be taken into consideration which limit the choice of the control algorithm. First, the operators of the algorithm will most likely be first level control engineers who rarely have more than a basic knowledge of control theory. Hence, it is preferable to choose a simple control technique that is easy to implement as well as whose development is straight forward. Despite the availability of a number of algorithms in the literature on compensation of nonlinearities arising from non-ideal behavior of the underlying system components, many of these approaches are general and not application specific. Moreover they are complicated and require an understanding that is beyond the theoretical background of a first level controls engineer. Further, the algorithm has to be implemented on a real-time platform and therefore it needs to be executed within one sampling period which is typically of the order of 5 to 10 milliseconds in a web application. Also the algorithm must be adequately robust such that it need not be continuously monitored and tuned. These are the main constraints in the design for a feasible control algorithm.

The choice of specific model based control techniques is not an option given the constraints introduced previously. In fact the models for transport in the presence of non-ideal rollers are complex and often require the use of intense numerical algorithms that are not well suited for a real-time application. For this reason the focus in this paper is on the design that includes adaptive algorithms.

The compensation of tension oscillations due to eccentric roller is considered first. Eccentricity compensation is a common problem in rotating mechanical systems and therefore, there has been existing work addressing this problem. Some of the algorithms are considered and among those the adaptive feed-forward (AFF) algorithm is elected to be the best fit for eccentricity compensation. Several adjustments to the original algorithm are presented for application to the web handling machine and to achieve better reduction of tension oscillations. The second part of this paper shows how the same algorithm can also be used for attenuation of tension oscillations due to out-of-round rolls. Lastly, the designed algorithm can be used in web lines where the source of tension oscillations is not known, that is, this algorithm is not specific to tension oscillations originating from non-ideal rollers.

CONTROL ALGORITHMS FOR ECCENTRICITY COMPENSATION

The presence of eccentricity is common in rotating machines. Examples include: engine noise in turboprop aircrafts [1] and automobiles [2], ventilation noise in Heating, Ventilation and Air Conditioning Systems [3], and many more. Several studies on control algorithms for the compensation of eccentricity can be found in the literature. For example, [4] proposes an adaptive algorithm for the compensation of eccentricity. The authors first included in the system an internal model of the eccentricity, designed an observer for the extended system, and then proposed an adaptation law for the estimation of the frequency of the eccentricity. In [5] the authors propose the use of repetitive control for eccentricity compensation in rolling; computer simulations are shown to illustrate the effectiveness of repetitive control in rejecting oscillations but no experimental results are provided. In [6] more details on repetitive control for nonlinear systems can be found, and in [7] the use of repetitive control for state dependant disturbances rejection is discussed. In [8] a nonlinear PI controller for controlling an uncertain system is introduced; one of the applications of the controller presented in the paper is eccentricity compensation. These algorithms are computationally complex and have been found to be difficult to adapt for use in web lines.

One important aspect in the compensation of eccentricity is that it is a state dependant disturbance and not an exogenous time dependant disturbance. Therefore, even if the resulting effects of eccentricity on the output are periodic oscillations, the techniques available for exogenous disturbance rejection cannot be used. However, under certain circumstances eccentricity appearing in the governing equation may be approximated by an exogenous disturbance. Consider a simple model for a motor with eccentricity

$$\begin{aligned} \dot{\theta} &= \omega, \\ J\dot{\omega} &= -b\omega - mge\sin(\theta) \end{aligned} \tag*{\{1\}}$$

where J is the inertia of the motor, b is the viscous friction coefficient, m is the mass of the motor, g is the acceleration due to gravity and e is the amount of eccentricity. If the motor speed is regulated at a reference value ω_r, it is possible to define the angular displacement error e_θ by

$$e_\theta = \theta(t) - \omega_r t. \tag*{\{2\}}$$

Using $\{2\}$ the eccentricity term can be written as

$$\begin{aligned} mge\sin(\theta(t)) &= mge\sin(\omega_r t + e_\theta) \\ &= mge(\sin(\omega_r t)\cos(e_\theta(t)) + \cos(\omega_r t)\sin(e_\theta(t))) \\ &\approx mge\sin(\omega_r t) \end{aligned} \tag*{\{3\}}$$

Under the assumption that the regulation error $e_\theta << 1$, the eccentricity term as above may be approximated with an exogenous time dependant disturbance and classical techniques may be considered for disturbance rejection.

The most established technique for exogenous disturbance rejection is the use of internal model of the disturbance in the controller [9]. The internal model principle states that in order to reject an exogenous disturbance it is sufficient to have a model of the disturbance in the controller under the constraint that the resulting closed loop system is stable. Hence, rejection of sinusoidal oscillations requires the inclusion of a model of the sinusoidal disturbance in the controller which means adding two complex conjugate poles on the imaginary axis of the complex plane at the frequency of the sinusoidal disturbance. Despite this technique is well known and well understood, it has a disadvantage. The addition of marginally stable poles in the controller results in ensuring the stability of the overall system more difficult to the point that, if disturbances at multiple frequencies are present, a simple PI might not be enough to stabilize the overall system. For these reasons the adaptive feed-forward is considered instead.

The adaptive feed-forward (AFF) algorithm is based on a simple idea: use an adaptive algorithm to estimate the amplitude and phase of the disturbance and feed-forward a control action equal and opposite to the estimated disturbance. Early work on the AFF algorithm can be found in [10, 11], in which the authors describe stability and robustness

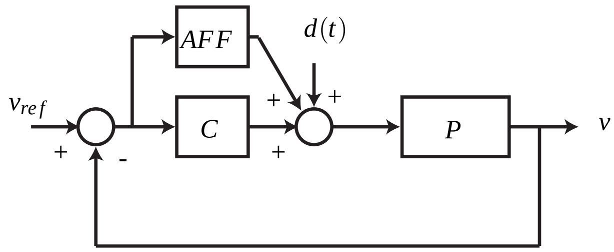


Figure 1: Adaptive feed-forward control scheme.

of the algorithm. Consider a system such as the one in Fig. 1 and assume that the disturbance $d(t)$ is in the form

$$\begin{aligned} d(t) &= A\sin(\omega t+\phi) \\ &= A\sin(\phi)\sin(\omega t)+A\cos(\phi)\cos(\omega t) = A_1\sin(\omega t)+A_2\cos(\omega t). \end{aligned} \quad \{4\}$$

The AFF algorithm uses the output error to estimate A_1 and A_2. Let the estimates for the parameters A_1 and A_2 be denoted by θ_1 and θ_2, respectively. The adaptation laws for the parameters θ_1 and θ_2 are

$$\begin{aligned} \dot\theta_1 &= g_1 e(t)\sin(\omega t), \\ \dot\theta_2 &= g_1 e(t)\cos(\omega t) \end{aligned} \quad \{5\}$$

where $e(t) = y_r - y(t)$ is the output error and g_1 is the adaptation gain. The feed-forward part of the algorithm is

$$u_{ff} = -\theta_1\sin(\omega t) - \theta_2\cos(\omega t). \quad \{6\}$$

The adaptive algorithm may be explained in the following manner. The adaptive parameter θ_1 is initialized to zero. If the output error has a sinusoidal component at the frequency ω, i.e., $e(t) = \overline{e}(t) + e_{A_1}\sin(\omega t)$, the product $e(t)\sin(\omega t)$ will produce a term $e_{A_1}\sin^2(\omega t)$ which is positive and will therefore increase the estimation parameter θ_1. As θ_1 increases the effect of the disturbance starts decreasing until θ_1 reaches the amplitude of the disturbance A_1. At that point the output error will not have any more sinusoidal components at the frequency ω since the disturbance is fully compensated by the term $-\theta_1\sin(\omega t)$ in u_{ff}. With the disturbance compensated, the integral of product $e(t)\sin(\omega t)$ will be zero over a period and hence the estimation parameter θ_1 will remain constant. The same reasoning applies for θ_2.

The control algorithm given by {5} and {6} is the AFF algorithm in its simplest form. In [12] the authors introduce a modified version of the AFF algorithm which includes a phase shifter. The phase shifter helps in increasing the stability margin of the AFF and reduces the adaptation time. The implementation of the phase shifter requires the knowledge of the transfer function between the disturbance and the control input or at least the value of the transfer function at the frequency of the disturbance. The algorithm for the modified AFF is

$$\begin{aligned} \dot\theta_1 &= g_1 e(t)\sin(\omega t+\phi), \\ \dot\theta_2 &= g_1 e(t)\cos(\omega t+\phi) \end{aligned} \quad \{7\}$$

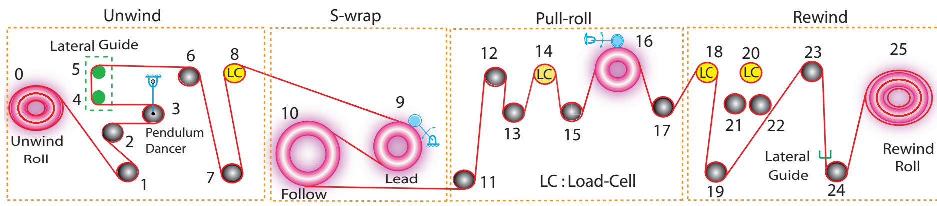


Figure 2: The Euclid Web Line (EWL).

where $\phi = \angle P(j\omega)$ is the phase of the process transfer function at the frequency of the disturbance.

Several versions of the AFF for cases where the frequency of the disturbance is unknown and time varying have also been developed; a complete discussion about these algorithms can be found in [13]. This is not a concern for the web handling application since the frequency of oscillation due to rotating machines is always known. In fact the frequency of the oscillations is equal to the rotational frequency of the machines or it is an integer multiple of this frequency. The rotational frequency of the machine can be obtained from velocity feedback for material rolls or computed from the line speed for rollers of known radius.

The AFF algorithm with a phase shifter is applied to a web handling case in [14]. In the paper the authors assume that the tension oscillations can be modeled as an input sinusoidal disturbance to the transfer function $G(s)$ from the torque input to the output tension. However localizing the entry point of the tension disturbances in the presence of a non-ideal roll it is not possible since the disturbance are a combination of several effects, therefore obtaining the transfer function between entry point of the disturbance and the tension is not possible. This is important since in order to use the phase shifted version of the AFF, it is necessary to know the exact transfer function from the disturbance to the output, otherwise the benefits of employing the phase shifter are lost and it could even lead to decreased performance of the AFF. In [15] a version of the AFF with an adaptive phase shifter is presented. In this case the adaptation algorithm not only adapts to the sinusoidal disturbance amplitudes but it also adapts the phase shifter to identify the transfer function from the disturbance to the output. However, the AFF with adaptive phase shifter results in a more complicated algorithm which is counter to the original motivation of seeking a simple solution to compensate periodic oscillations. Hence, an AFF with adaptive phase shifter is not considered in this study.

After an extensive literature review and a number of experiments on a web handling platform, the Euclid Web Line (see Fig. 2), using various approaches the authors arrived to the conclusion that the AFF in its basic form is the best suited control algorithm for the rejection of the oscillations due to eccentricity. Therefore, an adaptation of the basic AFF algorithm to web transport system is discussed in the remainder of the paper.

The EWL may be divided into four sections: unwind section, S-wrap section, pull-roll section, and rewind section. The two driven rollers in the S-wrap section are used to set the web speed and are generally referred to as the master speed rollers. The S-wrap rollers are under pure speed control, whereas the unwind, pull-roll and the rewind rolls have an

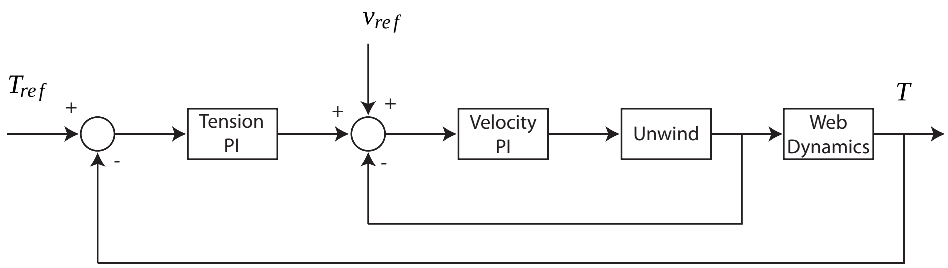


Figure 3: Two loop control scheme: the inner speed loop is used to regulate the angular velocity of the unwind roll and the outer tension loop provides correction to the reference velocity to maintain prescribed tension. This is often referred to in the literature as speed-based tension control system. The unwind block represents the dynamics of the unwind roll and the web dynamics block represents the governing equation for web tension.

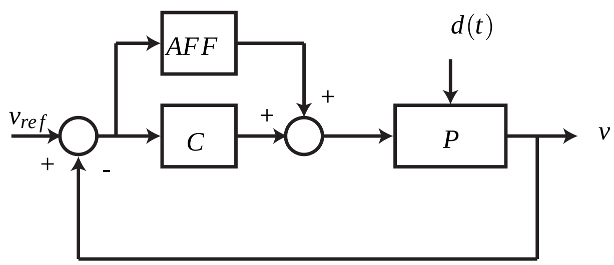


Figure 4: Adaptive feed-forward control scheme torque signal implementation.

inner speed loop and an outer tension loop as shown in Fig. 3 for the unwind section. In the EWL both S-wrap lead and follower rollers have some level of eccentricity. The initial step is to add the AFF to compensate for the oscillations in the roller velocity and study the effect of the attenuated velocity oscillations on tension oscillations.

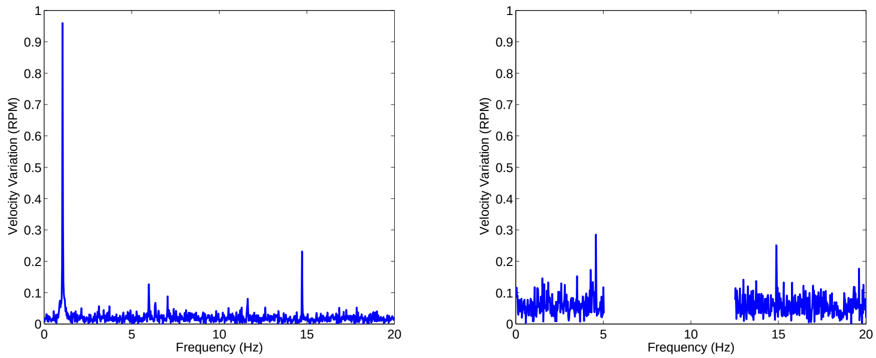
The AFF input is the velocity error and the output is a torque reference signal to the motor drive, see Fig. 4. The equations for the AFF algorithm are

$$\begin{aligned} \dot{\theta}_1 &= g_1(v_r - v_{Sf})\sin(\omega t), \\ \dot{\theta}_2 &= g_1(v_r - v_{Sf})\cos(\omega t), \\ \tau_{ff} &= -\theta_1\sin(\omega t) - \theta_2\cos(\omega t) \end{aligned} \quad \{8\}$$

where v_r is the line velocity reference, v_{Sf} is the velocity of the S-wrap follower, ω is the frequency of the disturbance that is being attenuated, τ_{ff} is the feed-forward torque signal generated for the drive, and g_1 is the adaptation gain. The AFF is designed to attenuate the fundamental frequency of the oscillations which is given by

$$f = \frac{v}{\pi D} \quad \{9\}$$

where v is the web velocity and D is the diameter of the roller.



(a) FFT of the S-wrap follower velocity with PI only. (b) FFT of the S-wrap follower velocity with PI and AFF.

Figure 5: Comparison between FFT of S-wrap follower velocity for PI only and PI+AFF.

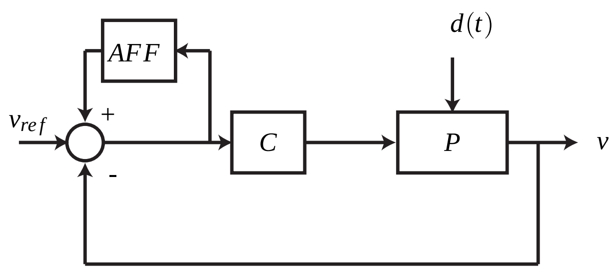
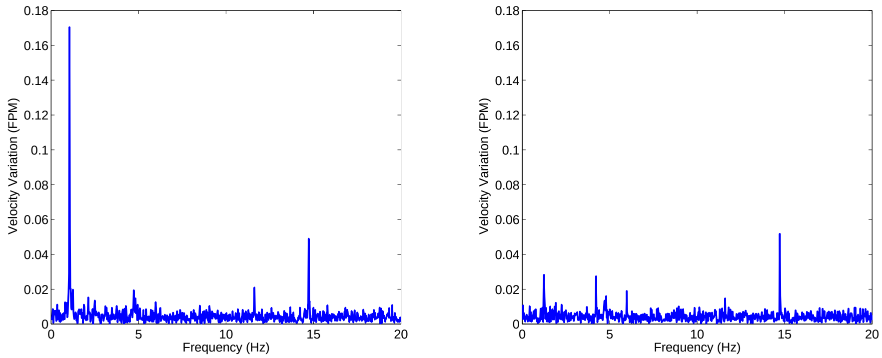


Figure 6: Adaptive feed-forward control scheme.

The tuning procedure for the gain of the AFF is simple and a direct consequence of the stability proof of the AFF algorithm [13, 16]. It is proven that the AFF is stable as long as the underlying process is stable and the adaptation gain is small. Based on that the AFF is tuned by starting with a very small gain and increasing it until a good performance is achieved.

Figure 5 shows the comparison of the Fast Fourier Transform (FFT) of the velocity signal of the S-wrap follower with and without the AFF and with a reference velocity of 200 FPM. First, note that the fundamental frequency of the disturbance is practically eliminated. However, a slight increase in the amplitude over the whole spectrum is also shown in the plot. This is because the AFF is generating a torque signal which is input to the motor drive. It is well known in the web handling community that the performance of the motor drive for tracking torque reference is not comparable to the performance of the same drive when tracking a velocity reference.

To avoid this problem the AFF can be used to generate a velocity reference instead of



(a) FFT of the S-wrap follower velocity with PI only. (b) FFT of the S-wrap follower velocity with PI and AFF.

Figure 7: Comparison between FFT of S-wrap follower velocity for PI only and PI+AFF with feed-forward signal on velocity reference.

torque reference, see Fig. 6. The equations for this new version of the AFF are

$$
\begin{aligned}
\dot{\theta}_1 &= g_1(v_r - v_{Sf})\sin(\omega t), \\
\dot{\theta}_2 &= g_1(v_r - v_{Sf})\cos(\omega t), \\
v_{ff} &= -\theta_1 \sin(\omega t) - \theta_2 \cos(\omega t)
\end{aligned}
\qquad \{10\}
$$

where the output of the AFF is now a reference velocity correction to the drive. The reason why the AFF is originally used to generate a compensating torque signal is because of the expectation that it can directly cancel the effect of the torque due to eccentricity using the torque generated by the drive. However, this is not necessary. Assuming that the torque due to eccentricity τ_e can be approximated by

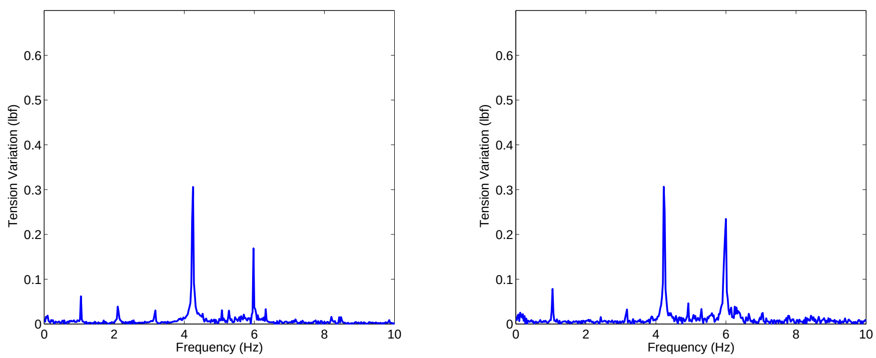
$$\tau_e = A\sin(\omega t + \phi) \qquad \{11\}$$

and the transfer function of the PI controller is $C(s)$, when using the AFF to generate a velocity reference as in Fig. 6, the AFF output u_{AFF} will converge to

$$v_{ff} = \frac{1}{|C(j\omega)|} A\sin(j\omega + \phi - \angle C(j\omega)) \qquad \{12\}$$

as opposed to $-\tau_e$. The signal v_{ff} in the input to the controller will produce an output equal and opposite to τ_e and hence compensation will be achieved in the same manner as in the previous configuration. Using similar arguments one can state that the AFF can be added at any point in the control loop as long as the path between that point and the entry of the disturbance into the system is composed of linear systems.

Figure 7 shows the FFT of the velocity signal with the AFF output as a velocity correction. Comparison of results shown in Fig. 7(b) and Fig. 5 indicates that in both cases the AFF effectively attenuates the velocity oscillations, but Fig. 7(b) shows no



(a) FFT of the tension in the Pull-Roll section with S-wrap follow on PI only.

(b) FFT of the tension in the Pull-Roll section with S-wrap follow on PI+AFF.

Figure 8: Comparison between FFT of the tension in the Pull-Roll section for S-wrap with PI only and PI+AFF with feed-forward signal on velocity reference.

increase in the base line oscillations compared to Fig. 5(b). Figure 8 shows the FFT of the tension signal in the pull-roll section of the EWL with and without the AFF for the compensation of the eccentricity in the S-wrap follower. The figure shows how the compensation of the eccentricity in the S-wrap has little effect on the tension signal. In fact only the second harmonic is attenuated. Note that the pull-roll section is chosen because in this section tension oscillations are mainly due to the eccentricity of the S-wrap follower and therefore the effect of the AFF would be more evident compared to the unwind zone where tension oscillations are due to both the eccentricity of the S-wrap lead roller and out-of-roundness of the unwind roll.

The addition of the AFF in the velocity loop, despite good attenuation of the oscillations in the velocity signal, did not improve the tension signal as expected. With similar arguments as the ones presented in $\{3\}$ one can assume that the oscillations in tension can also be approximated by an exogenous sinusoidal disturbance. Under this assumption the AFF can be used to attenuate such oscillations. This new configuration of the AFF is shown in Fig. 9 and the equations are

$$\begin{aligned} \dot{\theta}_1 &= g_1(t_r - t_{pr})\sin(\omega t), \\ \dot{\theta}_2 &= g_1(t_r - t_{pr})\cos(\omega t), \\ v_{ff} &= -\theta_1 \sin(\omega t) - \theta_2 \cos(\omega t) \end{aligned} \qquad \{13\}$$

where t_r is the tension reference and t_{pr} is the tension feedback from the pull roll section. Figure 10 shows the comparison of the FFT of the tension with and without the AFF with the line speed of 200 FPM. It shows that the AFF achieves very good attenuation at the fundamental frequency and at the second and third harmonics. A discussion on how the higher order harmonics are generated as a consequence of the interaction between the tension disturbance at the fundamental frequency and the disturbance in web velocity is given in [17]. Therefore, by reducing the disturbance at the fundamental frequency,

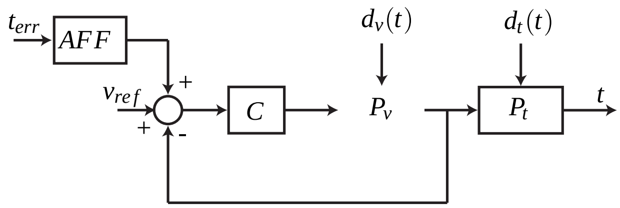
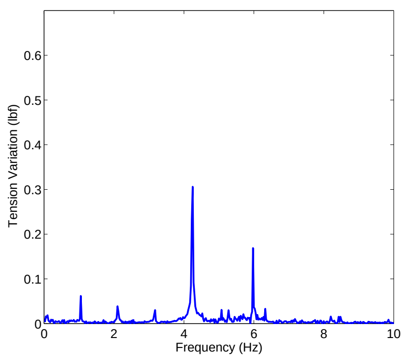
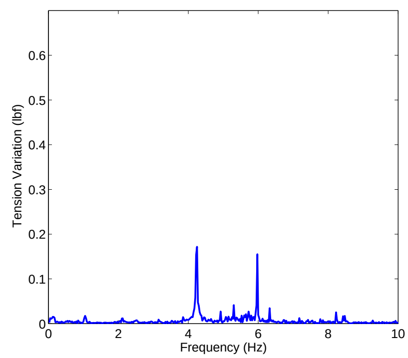


Figure 9: Adaptive feed-forward control scheme.



(a) FFT of the tension in the Pull-Roll section with S-wrap follower on PI only.



(b) FFT of the tension in the Pull-Roll section with S-wrap follower on PI+AFF.

Figure 10: Comparison between FFT of the tension in the Pull-Roll section for S-wrap with PI only and PI+AFF with AFF using tension error.

higher order harmonics are attenuated as well.

The AFF satisfies all the constraints described in the introduction and is efficient in compensating tension and velocity oscillations in the case of the presence of an eccentric roller. The following section describes the application of the AFF to the case of an out-of-round material roll.

ATTENUATION OF TENSION OSCILLATIONS DUE TO AN OUT-OF-ROUND MATERIAL ROLL

The problem of compensating tension oscillations due an out-of-round material roll is similar to the case of the eccentric roller. However, one major difference is that while the frequency of the disturbance induced by the presence of an eccentric roller remains constant over time, the frequency of the disturbance associated with an out-of-round material roll changes with decrease in roll diameter. The equation used for the computation of the fundamental frequency of the disturbance in $\{9\}$ for the case of the eccentric roller is also applicable to the out-of-round roll, but now the diameter of the roll is time varying making the frequency of the disturbance also time varying.

The AFF algorithm is originally intended for the compensation of sinusoidal disturbances with constant frequency. However, in [13] it is shown that the algorithm can also be used when the frequency is time varying if the rate of change of frequency is small. The frequency of the disturbance generated by an out-of-round roll {9} and its rate of change depend on two factors: the line velocity and the diameter of the roll. The frequency of the disturbance is varying slowly if the line speed is slow or if the roll has a large radius, in these cases the AFF can be used for the attenuation of disturbances. This might seem too restrictive but there is another aspect to be considered: disturbances at low frequencies are more critical than those of higher frequencies. The system of web spans and idle rollers naturally behave as a low pass filter and reject high frequency disturbances as the web is transported. On the other hand, low frequency disturbances are not attenuated significantly and if no action is taken they can propagate downstream and affect processes downstream. Therefore, the AFF can be used effectively because the disturbance with low frequencies that need to be rejected are generated in the presence of rolls with large radii or for web lines with low speed.

The AFF algorithm, similarly to the case of the eccentric roller, has tension error as input and generates a speed reference correction. It is assumed that the tension oscillation can be considered as an exogenous disturbance, as was done previously. The equations describing the AFF algorithm are

$$\begin{aligned}\dot{\theta}_1 &= g_1(t_r - t_{un})\sin(\omega t),\\ \dot{\theta}_2 &= g_1(t_r - t_{un})\cos(\omega t),\\ v_{ff} &= -\theta_1\sin(\omega t) - \theta_2\cos(\omega t).\end{aligned} \tag*{\{14\}}$$

Figure 11 shows the overall control scheme for the unwind roll with the AFF placed in parallel with the PI controller for tension regulation. In the figure multiple AFF blocks are added in parallel. In the presence of an out-of-round material roll, attenuation of the signal component at fundamental frequency does not produce attenuation of higher order harmonics as in the case of the eccentric roller. Therefore, it is necessary to add extra AFF blocks for the harmonics that need to be attenuated.

To test the algorithm the unwind roll is made purposely out-of-round by winding the web over a stack of paper; three different shapes of the out-of-round roll are used for testing:

- Shape 1: roll with flattened bulge (Fig. 12(a)). This shape is meant to resemble a flat spot
- Shape 2: roll with a bulge (Fig. 12(b)). Rolls might bulge due to gravity when they are suspended for extended period of time on mandrels.
- Shape 3: asymmetric profile (Fig. 12(c)). This shape was used to test the algorithm when the roll has an asymmetric profile that induces oscillations with multiple frequencies.

Two different polymer materials are tested: Tyvek, a polymer material made by Dupont, and polyethylene. This is done to test the robustness of the algorithm to different

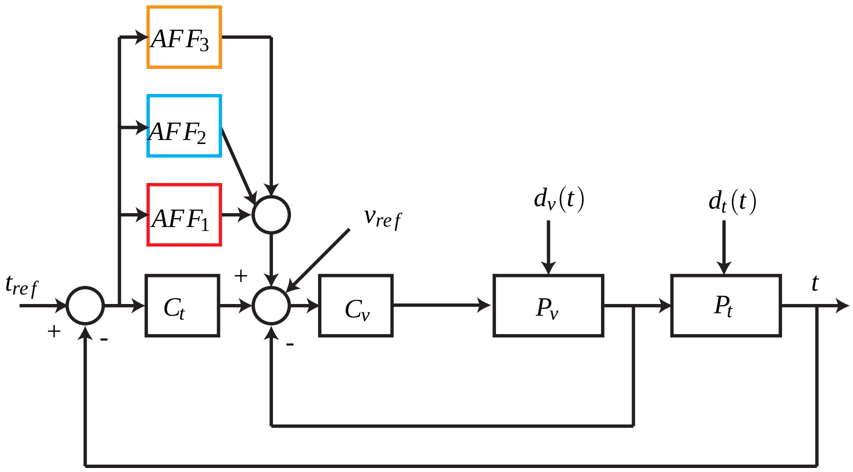


Figure 11: Adaptive feed-forward control scheme.

configurations, since it is possible to have web lines running different materials and out-of-round rolls can have different shapes. It is important to have a robust algorithm because it would be impractical in a production environment to adjust AFF gains when operating conditions change.

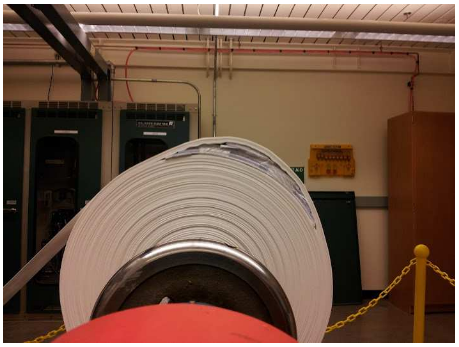
All the tests are performed with the web moving at 100 FPM, with a material roll radius of 8 in and with the gain of the AFF unchanged. Figures 13, 14, 15, 16 show the results of the tests. The plots show that AFF performed very well on the fundamental and first harmonic of the disturbance in all the scenarios while it is not effective on the second harmonic. The reason for this decreased performance for the second harmonic is that its frequency is moving at a faster rate compared to the fundamental frequency and the first harmonic, and hence, the AFF is expected to be less effective.

CONCLUSIONS AND FUTURE WORK

In conclusion the AFF is a simple and robust solution for attenuation of oscillations due to the presence of non-ideal rolls. It satisfies all the requirements discussed in the introduction. It is a simple algorithm that can be used by a first level control engineer or a line technician; it is not computational intensive so that it can be easily implemented on a real-time platform. It is also shown to be robust to different scenarios without the need for retuning of the adaptation gains with extensive experimentation on a web platform.

Implementation and testing of more sophisticated versions of the AFF may be considered as part of the future work. Also of interest is the analysis of the effect of the sampling period on the performance of the AFF, it is possible that a faster sampling time might improve the performance of the AFF for disturbances with fast changing frequencies. The adaptive feed-forward technique is presented as a feasible control scheme for attenuation of tension oscillations. Improvements to the implementation of the controller should be investigated to extend its application to high speed lines. Also,

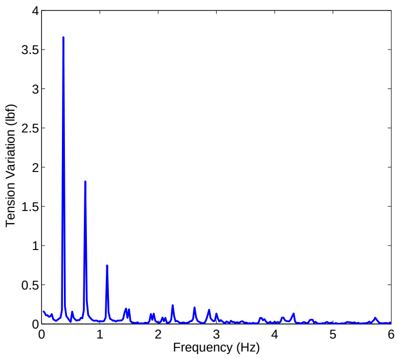
(a) Roll with a flattened bulge.



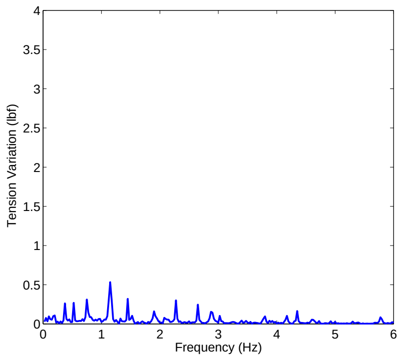
(b) Roll with a bulge.

(c) Asymmetric profile.

Figure 12: Roll shapes.

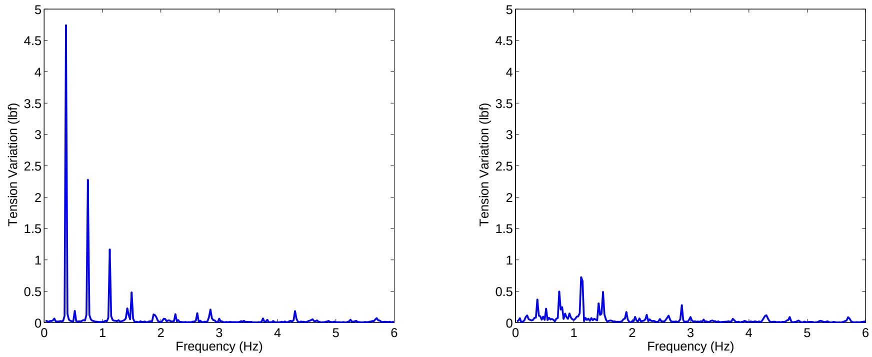


(a) PI only.



(b) PI+AFF.

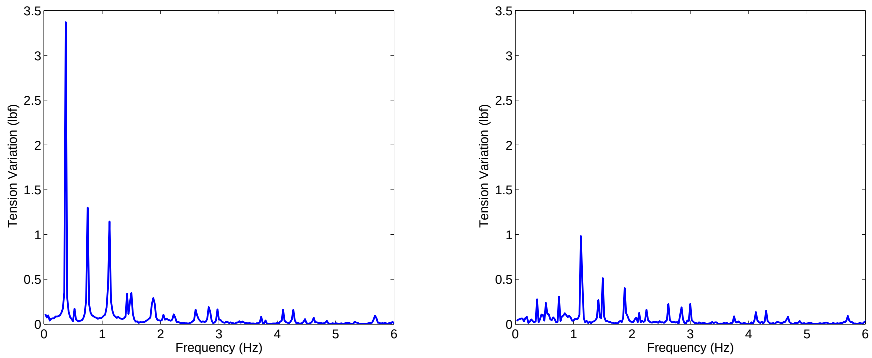
Figure 13: Comparison between FFT of tension for PI and PI+AFF implementation in the unwind section for roll shape 1.



(a) PI only.

(b) PI+AFF.

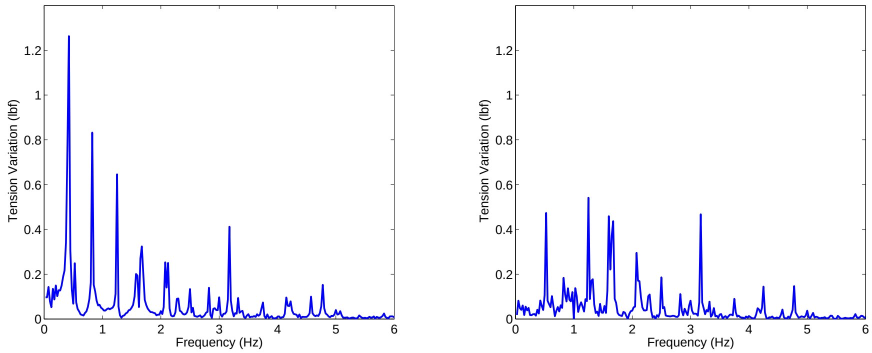
Figure 14: Comparison between FFT of tension for PI and PI+AFF implementation in the unwind section for roll shape 2.



(a) PI only.

(b) PI+AFF.

Figure 15: Comparison between FFT of tension for PI and PI+AFF implementation in the Unwind section for roll shape 3.



(a) PI only. (b) PI+AFF.

Figure 16: Comparison between FFT of tension for PI and PI+AFF implementation in the unwind section for roll shape 1 for polyethylene.

the AFF could be considered for compensation of periodic oscillations generated by other non-ideal components.

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