Disturbance Rejection in a Web Transport System Using a Pendulum Dancer

Benjamin Reish, Moad K. Abudia, and Karl N. Reid[1]

Abstract: *This paper focuses on the use of a pendulum dancer to remove disturbances in a web transport system. In an effort to emphasize the importance of first principles modeling of a web line, primitive elements are defined the facilitate developing a mathematical model of the system. The entry section of a typical roll-to-roll web line is modeled using a linearized span model. Comparisons are made of simulated and measured tensions to illustrate the effectiveness of a dancer and the efficacy of the model in different disturbance cases. The disturbance rejection ratio for the dancer is 80% for recorded data and 60% for simulated data.*

Introduction

Web processing lines must contain sub-systems which continually mitigate tension disturbances due to out-of-round unwinding rolls and eccentric idle and driven rollers. Such disturbances show up as variations in line speed and tension. A dancer sub-system, either translational or pendulum (also called rotational), can help mitigate a tension disturbance. The dancer may be passive or active. This paper focuses on the use of a passive pendulum dancer to reduce tension disturbances. A pendulum dancer is an idle roller attached to a moveable arm and is a part of a position regulating controller [1]. The force imbalance of the tension in the spans wrapped around the dancer roller and the input torque or force on the dancer arm causes motion in the dancer arm. The motion allows the dancer to smooth out tension variations in the line.

A literature survey is given to show the background of modeling web processing lines. Modelling web lines with primitive elements will be discussed as well as a description of the Euclid Web Line in the following section. After that, experiments using the Euclid Web Line are presented along with a tool for analyzing the recorded data. A bump on the unwind roller and an idler eccentricity are used as disturbances to the line that the dancer has to counter and then the dancer is removed for comparison purposes. Finally, the conclusions are given in the last section.

Basic elements used in web lines have been termed 'primitive elements'. These include the web spans, driven rollers, idle rollers, unwind rolls and rewind rolls. Each of these elements have specific 'parameters' that are sometimes shared among many elements and sometimes specific to one element. In a typical web line, the primitive elements are connected and therefore interact. Shelton discussed the transfer of strain (and tension) from one span element to the next [2]. Shin built on Shelton's work and was one of the first to document linearized models for a group of the primitive elements for typical

[1]The authors are with the School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, OK 74078. Corresponding author e-mail: ben.reish@okstate.edu

web lines [3] and those linear models are the starting point for this paper. Pagilla et al. developed a nonlinear span model in a web line accumulator and linearized the model to facilitate the study of accumulator dynamic behavior [4]. Carlson compared dancers to load cell control for tension regulation in [1]. Dwivedula studied the effects of active dancer elements as compared to passive ones in a web line [5]. Gassman et al. added a friction observer to model web tension and used it to estimate tension in an unmeasured span in [6], while constant bearing friction values are used in this paper. Gassman et al. developed a nonlinear model for a pendulum dancer using a summation of angles, and linearized the model for use in developing an H_∞ control scheme [7]. Branca et al. studied a nonlinear span element that, tied into a non-circular unwind roll, modeled the tension dynamics of the system in [8] using preprocessed span length derivatives while this paper calculates length online.

Models of the Primitive Elements in the Web Line

In order to create a simulation of the web line, primitive elements are used. These are first principles models of individual components in the web line. A roller is a primitive element which uses the torque balance of the torques applied by the incoming and outgoing webs and the roller radius (and the assumption of no slip). The web itself has to be modeled. The free span between two rollers is a primitive element modelled using conservation of mass to come to an equation relating tension in the span and velocity of the web entering and exiting the span and the tension in the previous span. As one might expect, these primitive elements can be linked together in such a way that the output of one element is the input to the next one to model the web traveling through the web line. See sources like [2], [3], and [4] for discussions on deriving the primitive elements used in this paper.

Euclid Web Line

The Euclid Web line in the Web Handling Research Center at Oklahoma State University is a roll-to-roll line which may be modeled using primitive elements. It is pictured in Figure 3 with the spans and rollers numbered in Figure 4. The unwind roll is controlled either using feedback tension from a load cell (at roller 9, t1) or dancer position (roller 4, Figure 3), and the rewind roll is controlled with tension feedback from a load cell (at roller 19, t3). The system modeled in this paper is the unwind section only: 10 rollers and 9 spans shown in the far left-hand box in Figure 3 and pictured in Figure 4. The web line is made up of several kinds of primitive elements: an unwind roll, idle rollers, a pendulum dancer (free moving or locked out), a load cell, and a driven roller.

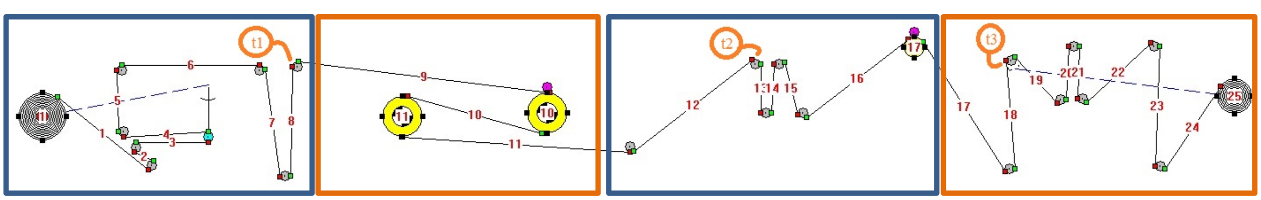

Figure 1: System schematic diagram with 4 sections from left to right: the unwind, the S-wrap, the pull roll, and the Rewind sections. T1-3 are the locations of load cells which are used for measurement and/or control.

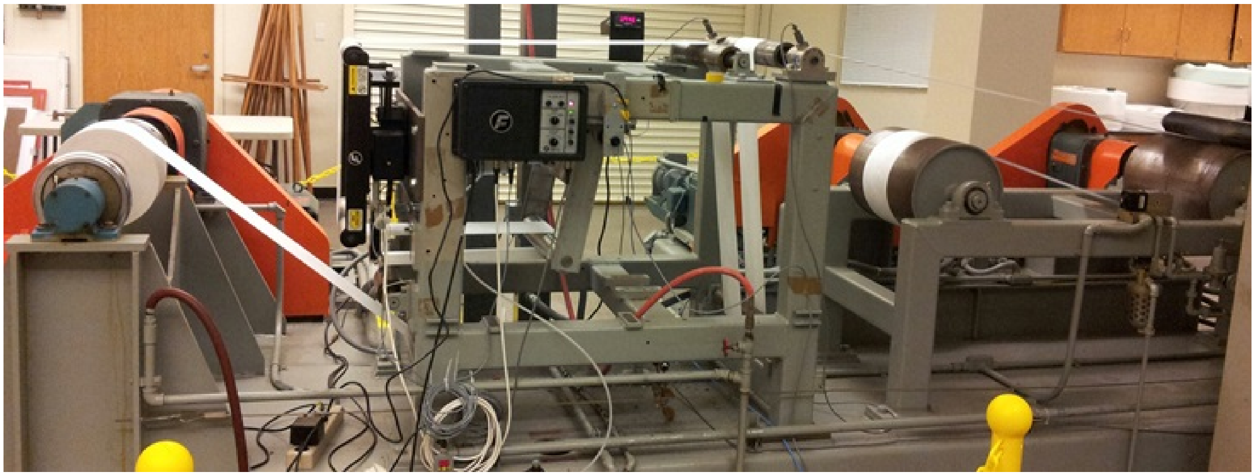

Figure 2: Unwind section of Euclid Web Line at Oklahoma State University. The unwind roll is at the left and the forward process direction is to the right, ending with the S-wrap (large rollers on the right).

Experimental Results

Using the load cell t1, the tension of the web can be recorded in real time. The measured tension shows if the web line is tracking a ramp start-up or if the tension is within tolerances in the vicinity of the load cell. To gain more information from the data, a tool called a Fast Fourier Transform must be used. It is a mechanism that takes a data set and attempts to fit a group of sinusoids to the raw time domain result. It calculates a group of frequencies and magnitudes of the sinusoid at those frequencies and returns the list of frequencies and magnitudes. With a little mathematical manipulation, this can be plotted and the plot shows the magnitude of oscillations at a given frequency. The plot can be quite helpful because the rotation rates of many components of the real web line are known or can be derived (see Table 1). Then the data can be plotted against frequency and the large magnitudes (peaks) can then be investigated. Finding a component of the line that operates at the frequency of the large magnitude will shine a light on possible culprit for that disturbance. In Figure 5 the largest peak is just a little past 2 Hz for the blue, 400 FPM data. Looking at Table 1, the S-wrap has a 1-per-rev frequency of 2.1 Hz at 400 FPM line speed. Thus, the probable cause of the peak in the data near 2 Hz is that one of the S-wrap rollers has a small eccentricity or miss-alignment or surface irregularity.

In Figure 5, the baseline tension, where no added disturbances are present, is shown to indicate that there are non-ideal effects in the web line under the best of circumstances and that the attempt to model the actual system does not include all those effects (and it may be difficult to do so). The simulation results are much smoother than the recorded data on the scale shown for the baseline run. The load cell at roller 9 is producing a noisy signal, but using the fast-Fourier Transform (FFT) method and Table 1,

Driver	200FPM	400FPM
Unwind	0.91 Hz	1.82 Hz
Idlers	4.24 Hz	8.48 Hz
S-wrap	1.067 Hz	2.1 Hz
Pull Roll	2.12 Hz	4.24 Hz

Table 1: 1-per-Revolution Frequencies for Given Elements

the 'noise' is due to several known frequencies: The S-wrap (roller 10) once-per-revolution (1-per-rev) frequency has a peak at both process speeds, which indicates an eccentricity in the roller. The idler 1-per-rev frequency is also evident at both process speeds, and for the 400 FPM speed, the pull roll (roller 17) 1-per-rev frequency shows up. This may be because the Pull roll is the master speed control for the Euclid line in this configuration. The peak at 39Hz may be a structural resonance, but that is to be determined. The peak at 60Hz indicates the load cell is not isolated well from the 60-cycle frequency of electricity. The 39Hz and 60Hz peaks will appear in all the measured tension plots. The 3Hz peak in the 400FPM data is a control system natural frequency. The 6Hz peak in the 200FPM data is a span natural frequency. From Figure 5, the model predicts oscillation (which is very small in magnitude on the scale used in the figure) for the baseline conditions which makes sense because it is a linear model with no disturbances.

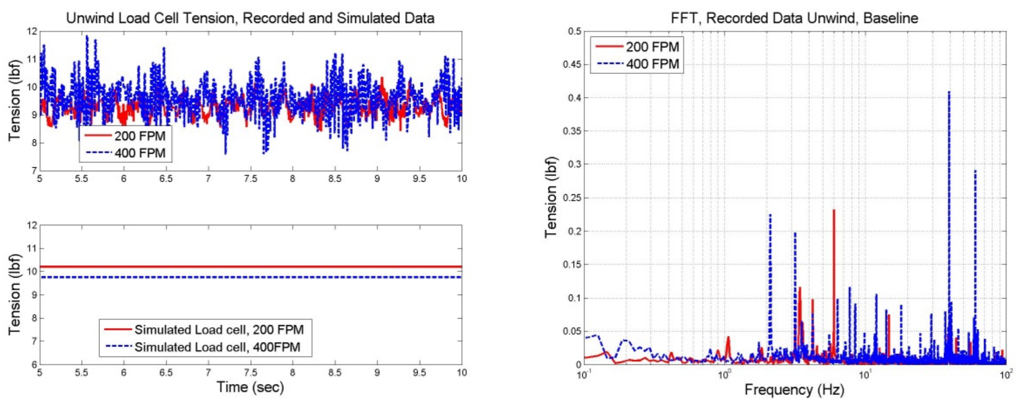

Figure 3: Baseline Tension, Recorded Tension (left, top), Simulated Tension (left, bottom), FFT (right). The simulation curves are offset artificially by adjusting the input force to the dancer in order to show the general character of both.

Time domain and FFT results from experimentation and simulation are presented. The baseline is the situation describing the default web line. For the Euclid web line, the line speeds are 200FPM and 400FPM, with a 14 inch unwind diameter. These two situations are the baselines (see Figure 5). The plots following them are of disturbed web lines where either a bump is introduced to the unwind roll or an eccentricity is introduced on an idler. The following plots have been scaled to the baseline by multiplying the magnitude of the response of the S-wrap 1-per-rev frequency in the baseline data and dividing the magnitude of the S-wrap response in the disturbed data since the S-wrap peak is not affected by the addition of disturbances but probably caused by an eccentricity. The peak caused by the S-wrap eccentricity should be the same magnitude in all the plots relative to process speed. The scaling is accomplished to ensure that comparisons from one run to the next are not biased.

Bump on the Unwind

After introducing a ¾ inch bump into the unwind roll, is recorded. The time domain and FFT responses are shown in Figure 6. The model is also set up with the initial conditions for a bump on the unwind roll. The simulation load cell tension FFT is displayed in Figure 7 and it is obvious that the simulation does not mimic the real system. The peak for the 1-per-rev frequency of the Unwind bump at 200FPM in the simulation is about 0.17 lbf while in the recorded data in Figure 6, it is almost 0.4 lbf. The simulation also shows a large peak at about 1.9Hz for the 200FPM data that is not just the first harmonic of the bump frequency, but is also the natural frequency of the control system. The recorded 200FPM data does not show that at all, but it does have a prominent peak at the first harmonic, 1.8Hz. Figure 6 shows peaks in the 200FPM data at 0.91Hz (unwind), 1.8Hz(first harmonic), 2.7Hz(second harmonic), 3.5Hz (span natural frequency), and 6Hz (span natural frequency). For 400FPM, peaks are located at 1.8Hz (unwind), 2.1Hz (pull roll), and 3.5Hz (span nat. freq.).

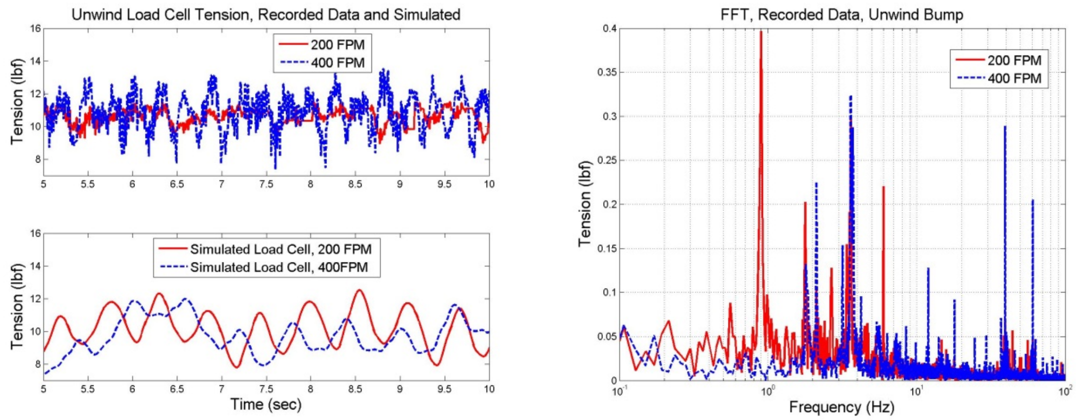

Figure 4: Unwind Roll Bump Disturbance, Recorded (left, top) Tension, Simulated (left, bottom), and Frequency Response (right). The Unwind 1-per-rev is a driver, but span natural frequencies show up.

Idler Eccentricity Upstream of the Dancer

Then an eccentricity is introduced at roller 2, an idler, which gives a high frequency driver for the dancer

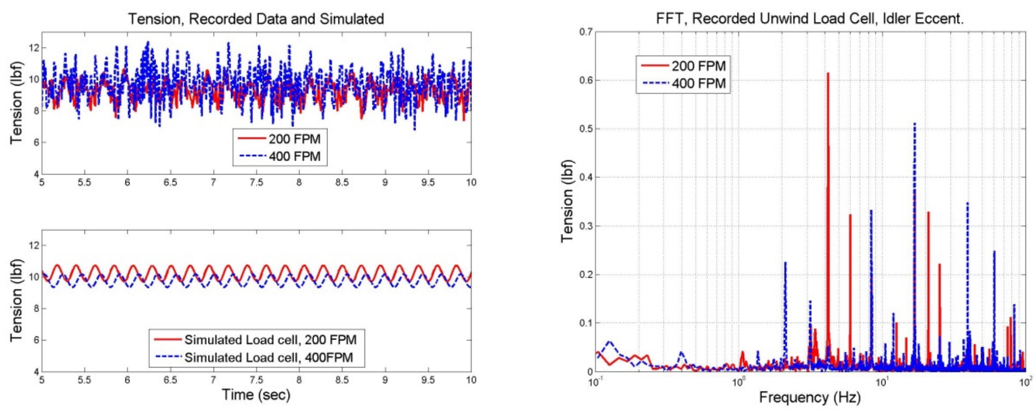

Figure 5: Idler #2 Eccentricity, Recorded Tension for 200 and 400 FPM process speeds (left, top), Simulated Tensions for the same (left, bottom), and FFT of Recorded Data (right). The idler frequency is the first large magnitude for both speeds.

to work out. The eccentricity is 0.1 inch on a 3 inch diameter roller. Thus, for the 200 FPM process speed, the 4.24 Hz frequency should be dominant and for the 400 FPM process speed, the 8.48 Hz frequency should become dominant. The idler chosen is roller 2 (see Figure 3), which allows the dancer to affect the disturbance. Figure 8 illustrates the recorded tension for the upstream eccentric idler and indicates the idler frequency is a driver for both process speeds. The simulations are more consistent and of smaller magnitude than the recorded data. Figure 8 shows peaks for 200FPM at 4.2Hz (idler), 8.4Hz (first harmonic), 12.6Hz, 16.8Hz, 21Hz, 25.4Hz (second-fifth harmonics), and 6Hz (span nat. freq.).

For 400FPM, the peaks are 2.1Hz (S-wrap), 8.4Hz (idler), 16.8Hz (first harmonic). The linearized model only produces one frequency for each process speed while the recorded data shows evidence of many more frequencies.

Eccentric Idler Downstream of the Dancer

Previously, the eccentric idler was placed before the dancer so that the dancer could affect the disturbance. Now, the eccentric idler is downstream of the dancer at roller 8 (see Figure 3). The

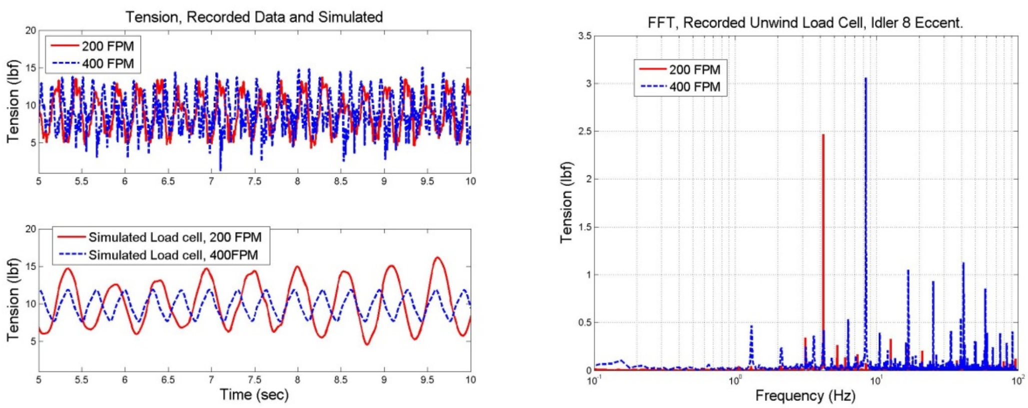

Figure 6: Eccentric Idler Downstream of the Dancer, Recorded Tension (left, top), Simulated Tension (left, bottom), FFT (right). Recorded data show a ~10 lbf peak-to-peak oscillation while the Simulation had near that for the 200FPM, but only about 5 lbf for the 400FPM case.

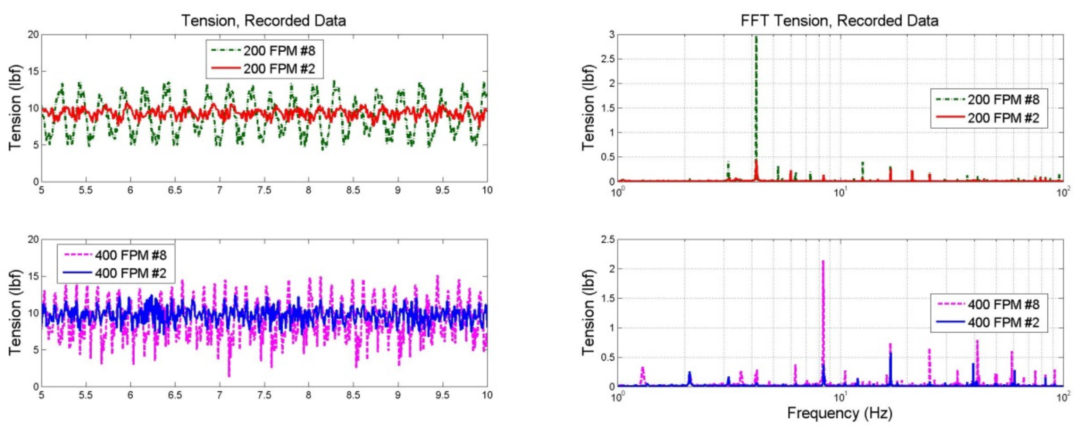

Figure 7: Eccentric Idler Upstream (#2) of the Dancer vs. Downstream (#8), 200FPM (left, top), 400FPM (left, bottom), FFT of 200FPM (right, top), FFT 400FPM (right, bottom). The dancer has a large impact on the load cell sensed tension. It removes 83% of the magnitude at the 1-per-rev frequency at 200FPM and 80% at 400FPM.

disturbance immediately hits the load cell and Figure 9 shows that the tension variation is large and the FFT shows more noise than previous situations. The 200FPM peaks are 3.1Hz (unknown), 4.2Hz (idler), 5.1Hz (span nat. freq.), 12Hz (unknown), 16.8Hz (fourth harmonic of idler). The 400FPM peaks from Figure 9 are 1.2Hz (unknown), 2.1Hz (S-wrap), 3.1Hz (unknown), 3.5Hz (span nat. freq.), 4.2Hz (pull roll), 6.1Hz (span nat. freq.), 8.4Hz (idler), 11Hz (span nat. freq.), 16.8Hz, 25.5Hz, 33.6Hz, 42Hz, 50.4Hz, 58.8Hz, 67.2Hz, 75.6Hz, 84Hz, and 92.4Hz (first-tenth harmonics of idler).

Figure 10 compares the two idler bump scenarios relative to process speed. Comparing a disturbance upstream of the dancer to downstream of the dancer, there is an 83% reduction in the magnitude of the idler 1-per-rev frequency for 200FPM and 80% reduction for the 400FPM.

Load Cell Feedback

Removing the dancer from the line by locking it out affective makes it just another idler. This leaves the Euclid line to be controlled with load cell feedback. The load cell used for measuring in the cases with a dancer is selected for control (roller 9). Using the same bump in the Unwind as before, data was recorded with load cell control. The recorded data takes on a different appearance compared to runs with a dancer (see Figure 11). The linear simulation does not follow that same pattern. From the FFT, the disturbance is from the Unwind which is as expected and is the case for both operating speeds.

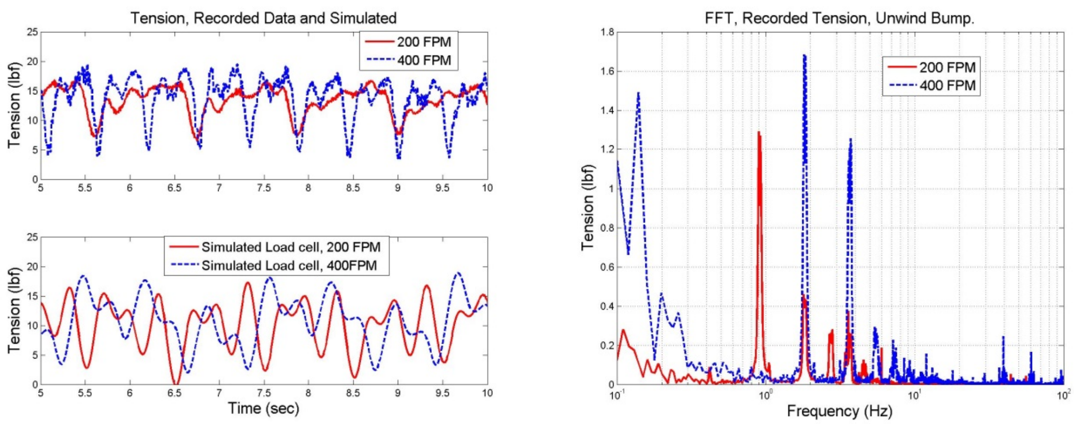

Figure 8: Unwind Bump Disturbance with No Dancer, Recorded Tension (left, top), Simulated Tension (left, bottom), FFT (right). The unwind 1-per-rev frequency (0.91Hz for 200FPM and 1.8 Hz for 400FPM) is clearly present as are several harmonics. The time domain data shows a slow oscillation at 400 FPM that shows up as low frequency peaks in the FFT.

Except for the low frequency oscillations, the other peaks in the FFT are the harmonics of the Unwind bump 1-per-rev frequency. The harmonics can be seen for each speed. The load cell control is allowing tension oscillations in the 10 lbf range. Compare that with the same Unwind bump using a dancer (Figure 6), where the tension oscillations were in the 6-7 lbf range. Figure 12 looks at the Unwind bump disturbance at 200FPM and 400FPM with and without the dancer. The time domain is zoomed in on a 5 second section to show differences in the response with and without the dancer. The FFT shows the same information, but it is easier to appreciate that the dancer removes 83% of the 1-per-rev frequency magnitude at 200FPM and 82% at 400FPM looking at the FFT. Figure 13 compares the simulation results for the Unwind bump disturbance and the simulation also show an 84% reduction in the magnitude of the 1-per-rev frequency for 200FPM and 61% reduction for the 400FPM case. At both speeds, the natural frequency of the dancer (0.42Hz) is evident (not so in the recorded data of Figure 6). The simulated no-dancer situation has a control system natural frequency at 0.48Hz and the other tall peaks for that situation are harmonics of the controller natural frequency. The 200FPM with-dancer simulation has a control system natural frequency at 1.72Hz which hits a harmonic of the dancer natural frequency and a resonant frequency of the idler subsystem. The 400FPM with-dancer plot shows several frequencies around the dancer natural frequency and then a fourth harmonic at 1.68Hz which is

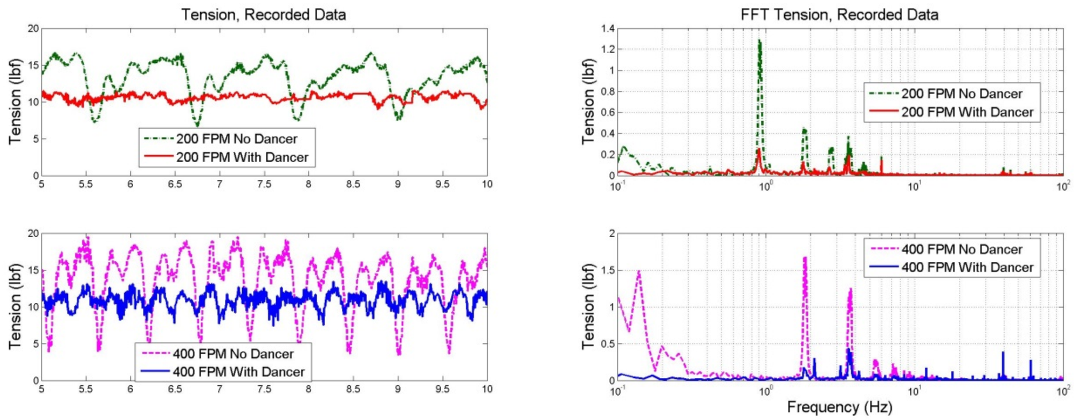

Figure 9: Comparing the Unwind Bump Disturbance without and with a Dancer. Without a dancer, the oscillations are much larger and sharper (note the zoomed in time scale). The dancer removes 83% of the 1-per-rev frequency magnitude at 200FPM and 82% at 400FPM.

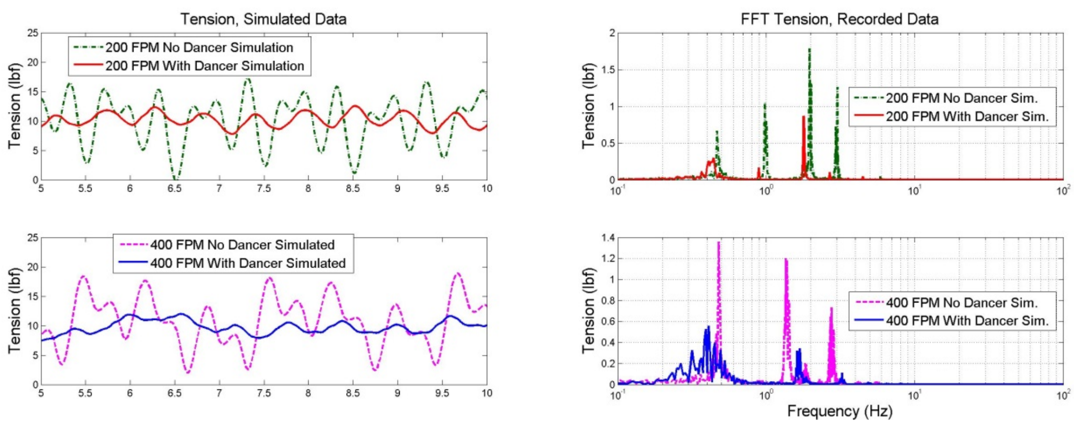

Figure 10: Comparing Simulations of the Unwind Bump Disturbance without and with a Dancer. The 200FPM simulation shows an 84% reduction in magnitude of the Unwind 1-per-rev frequency. The 400FPM simulation shows a 61% reduction at the unwind 1-per-rev frequency.

much larger than the unwind 1-per-rev at 1.82Hz. The 400FPM without-dancer plot shows peaks at 0.47Hz (controller nat. freq.), 1.3Hz (unknown), and 2.6Hz (first harmonic).

Conclusion

The Fast Fourier Transform is a tool that allowed sources of disturbance to be extracted from the load cell tension recorded data. This tool was used to compare several different circumstances occurring on the Euclid Web Line. Then, a simulation of the same web line was created from 'primitive elements'. The simulation results were shown alongside the experimental results.

The simulations are shown below the recorded time domain result for each situation in this paper. Qualitatively, the simulations don't have the same shape, but that is to be expected when using linearized models. They do agree with the recorded data that the dancer has a magnitude reducing effect on disturbances that occur upstream of the dancer. Quantitatively, the linear model does not mimic the real system. It is often smoother in response and of smaller magnitude than the real thing. This could be a good thing when designing model for model-reference control system. The limiting case may be the linearized models chosen for the simulations. Nonlinear models would allow for more variability and thereby give a more accurate result.

The experimental results showed that the dancer was highly effective in removing more than 80% of the magnitude of the oscillation at the 1-per-rev frequency of the unwind bump disturbance for both process speeds compared to not having one at all. The dancer also reduced the upstream eccentric idler 1-per-rev frequency oscillations by 80% when compared to the eccentric idler disturbance downstream of the dancer. The dancer an 80% rejection ratio for reducing disturbances that enter the line upstream of it in measured data and a 60% rejection ratio for the same in simulation.

Acknowledgements

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