# Tension prediction using web moving speed and natural vibration frequency

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## ABSTRACT

The characterization of web dynamics is critical for web handling and process control of roll-to-roll (R2R) manufacturing systems. One such critical characterization parameter is the tension in a moving web, which ultimately determines the efficacy of the printing process. Calculating web tension by out-of-plane vibration measurement offers a non-contacting and cost-effective solution to tension measurement during the R2R process. However, accurately modeling the tension by vibration and web moving speed is difficult, especially when the length-width ratio of a web span is low (<=3). Herein we present a learning-based prediction approach that uses the measurement of out-of-plane web vibration to derive tension in the moving web. We experimentally measured the out-of-plane vibration of short moving web spans in various scenarios by an optical fiber sensor. The sensor measures the out-of-plane displacement of the moving web wherefrom free vibration frequency can be extracted by a fast Fourier transform (FFT) algorithm. Given a set of (vibration frequency, tension, moving speed) measurement results, a learning model is trained for predicting the web tension for any pair of measured vibration frequency and moving speed. We tested the method in a R2R system. The tension prediction method is promising for measuring the tension of web spans in a R2R process.

***Keywords***: tension-speed-vibration, displacement sensor, FFT algorithm, roll-to-roll systems.

## 1 INTRODUCTION

The roll-to-roll (R2R) manufacturing systems are known for their higher efficiency of mass production than the batch processing system. Generally, a R2R machine conveys a continuous flexible web including thin plastic, metal, and paper through various R2R processing units, such as micro contact printing. Most R2R machines, such as flexible electronics printers, require precise and consistent moving speed and tensional force on the web. However, the web material inhomogeneity, motor torque variation, roller eccentricity, web sliding, rolling speed variation and air flow can cause undesirable tensional forces and motion on the web [1, 2], which can further lead to undesirable dynamic behaviors including web vibration, web wrinkling, edge cracks, and web misalignment. Hence, much research has been developed to measure and characterize these dynamic web behaviors for web handling and R2R process control.

In literature, the tensioned flexible string [3], beam [4, 5], plate [6] (considering the contribution of aspect ratio), and membrane [7] are the most common models of axially moving webs. Governing partial differential equations of motion can be obtained based on Newton's second law or Hamilton principle for the calculation of the out-of-plane displacement and the longitudinal displacement, as well the respective vibrations [8]. Furthermore, out-of-plane vibration and longitudinal vibration can be decoupled for a tensioned moving string model under a realistic assumption that there is no web speed change, no load on the web, and that the web tension remains constant [8]. From the derived out-of-plane vibration equations, the natural frequencies of either stationary or moving flexible webs can be calculated. The calculation results demonstrated that the out-of-plane vibration strongly depends on the tension and speed of moving webs, which was experimentally validated by the measurements in R2R test benches [8, 9]. In [8], the validation works well because the high length-width ratio (≥3) in their R2R bench fulfill the requirements of string modeling. In [9], they derived an approximate fitting formula among axial tension, web speed and natural frequency while the accuracy of the formula highly relies on the precision of the measured geometry and material parameters of web. To our knowledge, the related vibration study is yet to be carried out in the similar way. Furthermore, a shorter length-width ratio can change the natural frequency of the moving web by changing stiffness as well as compacting the R2R machine. Therefore, the investigation of the dynamics of the short web span significantly contributes to R2R systems, such as the R2R micro-contact printer [10].

This paper focuses on the sensing of out-of-plane vibration of short web span for non-contact estimation of tension. The tension-vibration-speed relations were learnt in a machine learning model for various web thicknesses. The trained learning architecture can be used to infer or predict tension for future measured vibration frequency and moving speed.

## 2 MATERIALS AND METHOD

Two types of PET webs were tested, as shown in Table 1. Web material properties and variables include mass density $\rho$, modulus of elasticity $E$, web width $w$, and web thickness $t$.

Using a displacement sensor, distance signals are acquired with a selected sampling interval $\Delta t$ (its inverse is the sampling rate $f_s$). According to Shannon Sampling Theorem, the most effective sampling rate of preventing an

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| Material types | $\rho$ (kg/m^3) | $E$ (Gpa) | $w$ (mm) | $t$ (µm) |
|---|---|---|---|---|
| Mylar PET 1 | 1390 | 4.8 | 101.6 | 101.6 |
| Mylar PET 2 | 1390 | 4.8 | 101.6 | 127 |

Table 1: Properties of web materials.

| | Static web | Moving web (254 mm/second) |
|---|---|---|
| Tension (N) | $f$ (Hz) | $f$ (Hz) |
| 20 | 82.16 | 82.16 |
| 30 | 100.63 | 100.63 |
| 40 | 116.20 | 116.20 |

Table 2: Natural frequencies of 101.6 um thick web for different tensions.

aliasing is at least double of the highest detected frequency. We use the analytical string model in [10] to estimate the fundamental natural frequency for choosing a suitable sampling rate of the displacement sensor. Table 2 is the

example of one calculated result. For all the setups in the paper (see section 3), the calculated frequencies were less than 200 Hz.

## 3 EXPERIMENTAL SETUP

A web material was mounted on a R2R machine, as shown in Fig. 1. To simplify the setup, we only used the web handling part of the machine, which is composed of two motorized rolls and two idler rolls. A ring rotation encoder and a readhead (RENISHAW MF100F and LM10) were mounted on the upper idler roll to measure the linear web moving speed. The measured speed is then used as a feedback signal to control the web moving speed. The bottom idler roll was a tension measuring roll (FMS RMGZ922) which measured the tension of the web for web tension control. In operation, it is desirable to control both the tension and the linear speed of the moving web at the same time. Thus, the unwind roll is controlled to maintain a constant linear web moving speed using the feedback signal from the encoder. In the meantime, the rewind roll is operated under torque control mode to maintain a constant tension of the web using the feedback signal from the tension measuring roll. The rotation encoder-readhead and tension measuring roll were both well calibrated before experiments. The variation of web tension and linear motion speed both can be controlled within the range of ±10%.

It is known that radii of the unwind roll and rewind roll change during R2R process. To eliminate its effect on the distance between the displacement sensor and the moving web we set up the displacement and vibration measurement on the web span between the two idler rolls to test as shown in Fig 1. The web span between the idler rolls has a

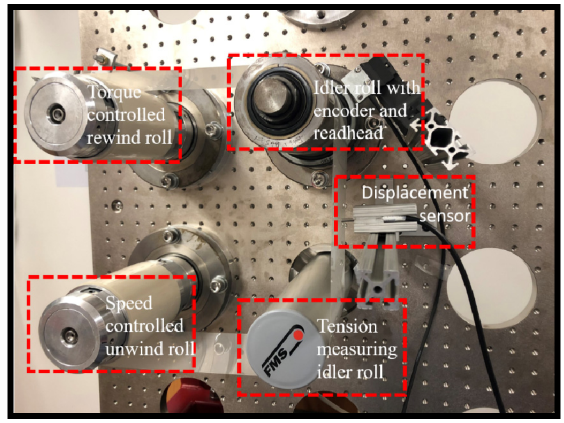


Figure 1: Experimental setup.

longitudinal length of 203.2 mm. Given a 101.6 mm wide web in this paper, the web span length-width ratio is 2. The probe of a displacement sensor was positioned about 3 mm away from the midpoint of the web span.

We used an optical fiber displacement sensor (muDMS-RC-100-T5) to measure the out-of-plane displacement of the moving web. This sensor transmits the light from one-fiber bundles and receives the reflected light from target, with second receiver which is randomly mixed with transmitter. The received light is processed ratio-metrically and converted to distance in the displacement measurement system. The sensor is reflectance compensated, and invariant of web surface variation during motion. In this paper, the sensor data is collected through a LabVIEW based built-in software to measure the frequency of the out-of-plane vibration of the web in stationary and moving states. The resolution and working range of this sensor are respectively 0.1 µm and 6 mm. The sampling rate of this sensor is based on the internal clock of 10.4KS/s with the maximum output rate of 5.2KS/s. The sensor has a mean average filter to smooth and under-sample readings together before sending the results to communication port (USB in this paper). Hence, the actual sample rate (readings/second) can be set by the width of the average filter, which is also the under-sampling rate. In this paper, we set up sampling rate at 640 Hz by selecting 16 as the width of average filter.

## 4 DATA PROCESSING

Fig. 2 shows an example of acquired displacements-time curve and amplitude-frequency curve when a 127 µm thick web is activated with 40 N tension on the web and 23.5mm/second web speed. To enlarge the amplitude of the vibration, we used a rubber mallet to hit the web. We can notice that when we hit the web, there is a huge transverse deformation on the web and the web starts to vibrate; then the amplitude of vibration decays with time as shown in the displacements-time curve. The measured out-of-plane web vibration is analyzed using FFT with a time window of 3.125 s, resulting in a frequency resolution of 0.32 Hz.

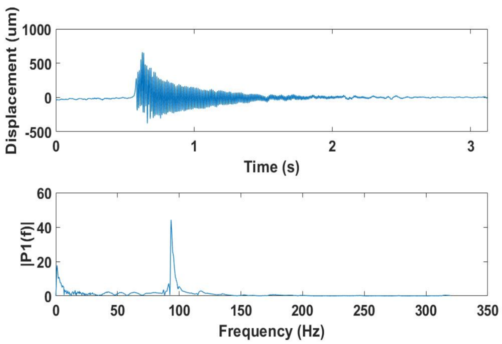


Fig. 2: Example of measured of the displacement and FFT result.

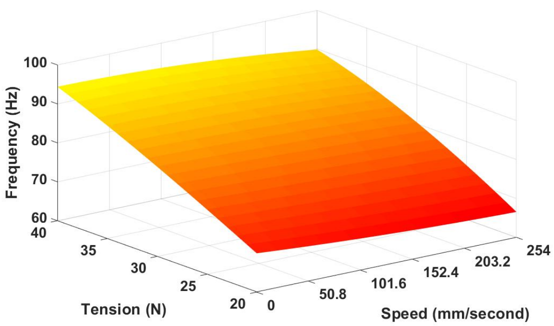


Fig. 3: Natural frequency for different combination of web tension and speed for 127 µm thick PET using polynomial curve fitting.

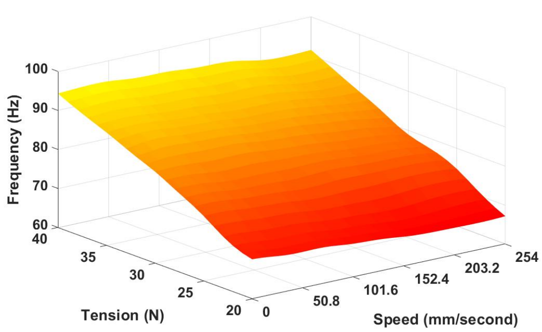


Fig. 4: Natural frequency for different combination of web tension and speed for 127 µm thick PET using ANN fitting.

From the FFT result, we can see that there is a high peak at 93.39 Hz which is the detected natural frequency.

To obtain sufficient data for training a machine learning model, experiments were performed in 198 different sets of conditions, i.e. all possible combinations of 2 different thicknesses, 11 different tensions and 9 different moving speeds. The acquired data are fitted using polynomial function and artificial neural network (ANN). The polynomial curve fitting with 3 degrees is applied. For the ANN fitting, a feedforward three-layer neural network is

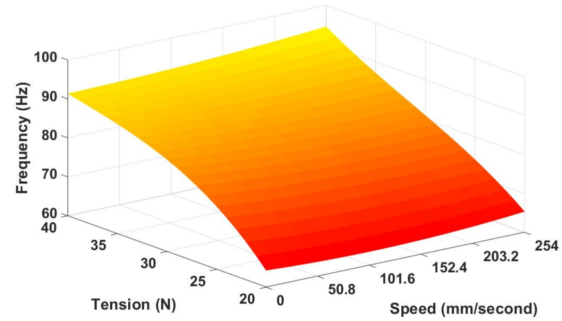


Fig. 5: Natural frequency for different combination of web tension and speed for 101.6 µm thick PET using polynomial curve fitting.

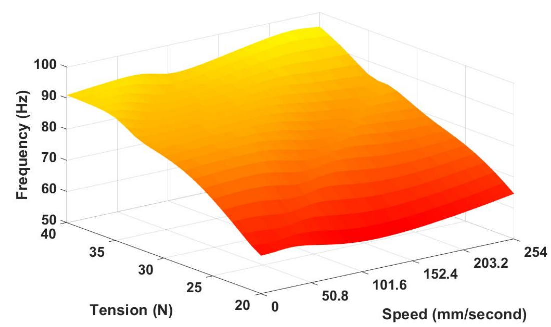


Fig. 6: Natural frequency for different combination of web tension and speed for 101.6 µm thick PET using ANN fitting.

used, which has 2 input nodes, 10 hidden nodes and one output node. The transfer functions in the input layer and hidden layer are *tansig* and *purelin*, respectively. Finally, we used 10-fold Cross-Validation to evaluate the performances of each method.

# 5 RESULT

In our experiments, the web span length-width ratio is low. Comparing our measured frequencies with the estimated natural frequencies in Table 2, we observe that the measured frequencies are significantly lower than the calculated frequencies from the analytical string model. In other words, string model is inappropriate for the web span of low length-width ratio.

Fig. 3-6 show the frequency prediction results for the combination of various web thicknesses, web speed and tension. For polynomial curve fitting, a 1.85% tension prediction error is obtained. For ANN fitting, the smallest prediction error of tension is 0.88%. Both results are far more precise than the desired industrial tension measurement, which is 10%-30% error. Hence, we can conclude that the learning-based methods can accurately

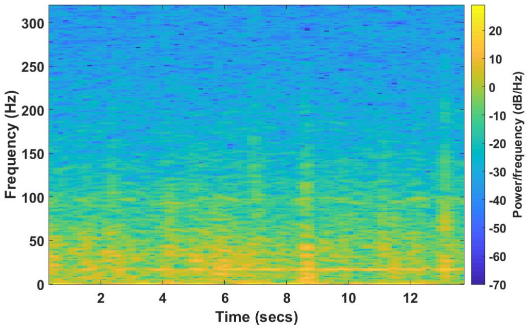


Fig. 7: Spectrogram of out-of-plane vibrations for 40 N tension and 76.2 mm/s web moving speed. The natural vibration frequency should be 93.76 Hz, but it's buried in noise.

predict web tension from measured vibration frequency and web moving speed. However, we should notice that the polynomial fitting curves are smoother than the curves of ANN, which indicates a possible overfitting in ANN results.

The ideal magnitude spectrum of an analyzed signal should be a spike at the natural resonance frequency. The frequency of the signal was recovered very well within the resolution, as shown in Fig. 2. However, the amplitude, which should be higher, was obtained with worse accuracy, due to the limitation of DFT such as the leakage (spread) to the adjacent frequencies and the effect of the discrete character. Meanwhile, forced frequencies are detected which mainly come from the rotation of the rollers. The angular speed of rollers is known to be low by calculation. It is then easy to ignore the weaker fundamental and harmonics of forced vibrations after exciting the web resonance.

## 6 CONCLUSION

In roll-to-roll micro-contact printing systems, quality and mass production is the goal of the process. To achieve this goal, stable and control operation of moving web is of great importance. Such operations could be possible only if tension-speed-vibration of moving web is thoroughly investigated. In this paper, the tension-speed-vibration of axially moving PET web are investigated by experiments, based on transverse vibrations. We test two tension prediction methods, including polynomial fit and artificial neural network (ANN) prediction, for a variety of moving webs of low length-width ratio. The web tension is accurately predicted (error < 10%) using the measured vibration frequency and web speed

We also investigated the possibility of a real-time application. For example, for an industrial implementation, the tension signals are used as online feedback signals for the web tension control. Thus, the tension must be calculated within a few milliseconds, by extracting out-of-plane web vibration frequencies using an FFT with time sliding window [8]. However, the resolution of FFT is in inverse proportion to the length of the time window. For commercial contacting tension measurement tools, like the tension measuring roll in our experimental setup, the sampling rate is 1 kHz. To achieve an equivalent sampling rate, the length of time sliding window should be at least 1 millisecond. In that case, the resultant frequency resolution of FFT is 1000 Hz, which is too large to achieve an accurate estimation of tension. According to our test results, to estimate a tension with an error within 10%, the frequency resolution of FFT must be less than 2 Hz. Also, we have noticed that in some situations, the amplitude of natural frequency is indistinguishable from noise, which makes the natural frequency nondetectable as shown in Fig. 7. However, this method can be considered as a complementary method to measure the web tension in cases where contact measurement methods are not available.

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