MEASUREMENT OF WEB TENSION DISTRIBUTION BY POINT SOURCE PULSE EXCITATION

by

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ABSTRACT

A web is a material that is produced as a continuous sheet and stored in wound roll form. Mechanics of web material handling in production, coating or conditioning, and winding operations affect web uniformity and the material stress/strain state, thus affecting roll quality. In an effort to improve all aspects of web handling procedures, much attention has been focused on acquisition and utilization of on-line web handling process information such as web tension. Tension is a quantity basic to web production and processing yet historically has been difficult to measure except in an average sense. Improvements in on-line tension measurement accuracy have foreseeable application to automated tension control systems and winder maintenance used in modern day web production/processing facilities. This paper describes a new means of noncontacting, local web tension measurement through use of a point source pneumatic excitation coupled to signal acquisition and processing schemes. Advantages of this new system include variable web excitation rate, variable system tuning for different applications, high lateral tension distribution resolution, and compact, easily serviceable transducer head assembly. This work was sponsored through the Web Handling Research Center (WHRC), an NSF funded research facility located at Oklahoma State University in Stillwater, Oklahoma.

NOMENCLATURE

C_{air}	Speed of sound in air (m/sec)
$C_{membrane}$	Speed of sound in tensioned membrane (m/sec)
Δf	Frequency domain resolution/increment (Hz)
f_{web}	Web flexural waveform characteristic frequency (Hz)
K_{air}	Wave number for air (m^{-1})

$K_{membrane}$	Wave number for in-vacuo membrane (m^{-1})
ρ_{air}	Density of air (kg/m^3)
$\rho_{membrane}$	Density of membrane (kg/m^3)
ρ_{web}	Density of web (kg/m^3)
r	Cross correlation shift index (Eqn. (3))
$\hat{R}_{xy}$	Sample cross correlation function
Δt	Web flexural waveform time of flight (sec)
T	Web tension (N/m)
T1	Time period in Figure 3 (sec)
T2	Time period in Figure 3 (sec)
T3	Time period in Figure 3 (sec)
T_s	Data sampling period (sec)
x	Transducer head microphone spacing (m)
x(n)	General transient data record (Eqn. (5))
$\tilde{x}(n)$	General periodic data record (Eqn. (4))
$\tilde{X}(k)$	Fourier transformed periodic data record (Eqn. (4))
x_n	Upstream system microphone data (Eqn. (3))
y_n	Downstream system microphone data (Eqn. (3))

INTRODUCTION

Much interest in local web tension measurement has developed in recent years. Precise knowledge of tension distribution across web spans could lead to more uniform web process control and thus to a more uniform, predictable end web product. Current tension measurement systems were not as versatile as required by some WHRC members. A variety of interests were maintained by WHRC members with respect to any new tension measurement system to be developed. Principal among requirements was that of web noncontact during operation. Furthermore, such a new system would be required to perform well on a wide variety of web materials over a wide nominal tension range. Thus, the tension measurement system would need to be adaptable to thin polyester film as well as thicker paper products, for example. Lastly, costs were to be held minimal in the finished tension measurement product.

PROJECT BACKGROUND

Noncontacting local, point tension measurements had heretofore been only approximated with currently available tension measurement systems. Most notable of these are the Altim Tensometer [1] and TENSCAN [2] tension measurement systems. Both of these systems utilize a loudspeaker and slot arrangement to provide a line excitation to the web under test, thus generating traveling waveforms. TENSCAN employs laser beams and the Altim Tensometer employs microphones in sensing these induced waveforms. Area web excitation is used in these cases rather than discrete point excitation. Transducer head size for these measurement systems was therefore larger than desired in this research with associated cost being substantially higher for the more elaborate transducing schemes. Through pros versus cons examination of these available tension measurement systems, project goals became geared toward development of a new system that would provide greater lateral tension distribution resolution while maintaining small transducer head footprint and low system costs.

The primary research objective was to create an impulsive yet noncontacting stimulus to the web. Air loaded membrane dispersive effects have been well documented [3] [4], in which air loading affects membrane waveform propagation speed as a function of excitation frequency. This effect could be reduced through use of high frequency web stimulus. Thus, coupling of a broadband impulsive input to a web was an original research concept in hopes of reducing air loading effects and thereby simplifying data processing and conversion.

A pneumatic web pulsing system was conceived to secure the desired noncontact web excitation aspect. Concepts from nonlinear acoustics were used wherein pneumatic pressure pulses would experience pressure front steepening through one dimensional propagation. Through this steepening process, a pressure pulse could be converted into a weak shock pulse. A hole was placed in a rotating disk to serve as the pneumatic pulse gating mechanism. Regulated air supply pressure was applied to one side of the disk and an outlet tube was attached to the other side of the disk. Overlap of the disk hole with the pneumatic manifolds resulted in a pressure pulse which would propagate along the outlet pulser tube length. Pressure front steepening occurred during this propagation process, culminating in a weak shock wave "snap" when the pressure front reached the pulser tube exit. This "snapping" pulse was applied to a web under test, generating traveling waveforms within the web. Figure 1 is an oscilloscope trace of this weak shock pulse sensed by an electret microphone. The 70 microsecond pulse duration indicated in Figure 1 would ideally result in a 14 kHz bandwidth input signal, which was believed to be of sufficient bandwidth to minimize air loading effects.

Sample web materials were tested with the pneumatic pulser, as shown schematically in Figure 2. Pneumatic shock tube exit and sensing microphones are situated in a mobile transducer head. Web flexural waveforms, generated through the weak shock pulse, would pass by the two microphones, thus providing an electrical output signal. Wave propagation speed could then be

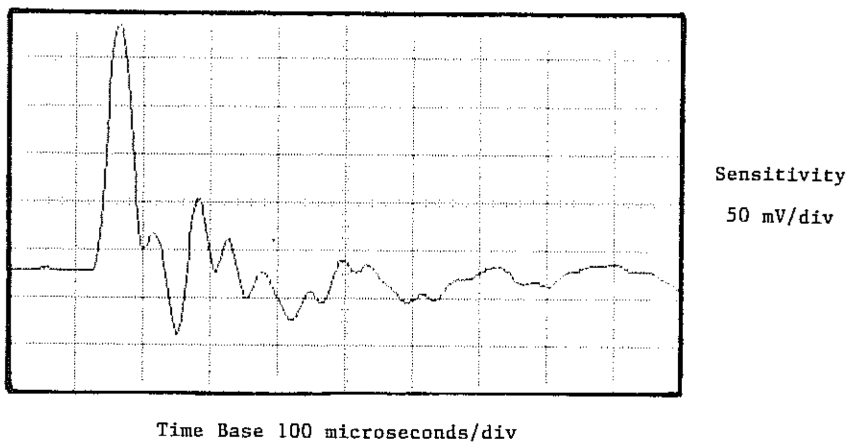

Figure 1. Oscilloscope trace of pneumatic weak shock pulse.

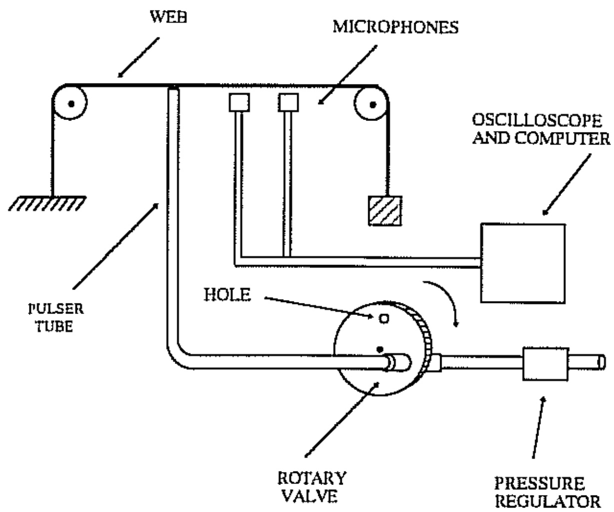

Figure 2. Schematic diagram of laboratory web testing facility.

related to web tension. Figure 3 is an oscilloscope trace from such a test that illustrates the complexity of this process. In the figure, three time periods have been marked. The region marked time period T1 represents microphone response to the broadbanded impulsive signal. For T1 = 160 microseconds and microphones two inches apart, this corresponds to a propagation speed of 12500 inches/second (317.5 m/sec), which is near the speed of sound in air. Time periods T2 and T3 correspond to web flexural waveform passage, which are the main signal portions of interest. Time period corresponding to flexural waveform formation and propagation to the first (upstream) microphone is given by the interval T2. For this distance being two inches and T2 = 390 microseconds, propagation speed is 5128 inches/second (130.2 m/sec). In comparison, waveform propagation in the web material is given by time period T3 where travel proceeds from the first (upstream) microphone to the second (downstream) microphone. For T3 = 760 microseconds and two inch microphone spacing, this propagation speed is 2632 inches/second (66.8 m/sec). The large difference in apparent propagation speed from intervals T2 and T3, nearly a two to one ratio, provides an illustration of the pulse to web coupling. Process of flexural waveform formation plus travel appears to occur much more quickly than resultant travel of a fully developed waveform. Note also the web flexural waveform gross period, which is inversely proportional to frequency. A rough estimate of the waveform characteristic frequency is 1200 to 2500 Hertz, which is a substantially lower frequency than that of the input pulse by itself. Due to the pneumatic shock pulse higher frequency components not being successfully coupled to the web, air loading effects were present and thus correction for air loading was required in tension calculations.

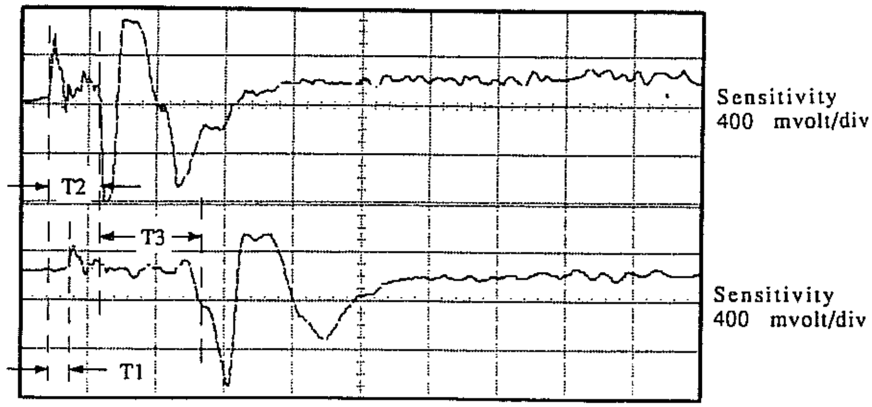

Figure 3. Oscilloscope trace of unfiltered web flexural waveform signal.

METHOD TECHNICAL REVIEW

The "Ribbon" equation is often used in applications where air loading effects membrane response. A frequency dependent air loading term is added to the in-vacuo membrane phase speed relation [4]:

$$T = C_{membrane}^{2}\left(\rho_{membrane} + \frac{2\,\rho_{air}}{\sqrt{K_{membrane}^{2} - K_{air}^{2}}}\right) \tag{1}$$

where K_{air}, $K_{membrane}$ and ρ_{air}, $\rho_{membrane}$ are wave numbers and density for air and membrane respectively. Measured variables in this tension measurement scheme were flexural waveform time of flight (Δt) and characteristic frequency (f_{web}). Written in terms of these variables, equation (1) becomes:

$$T = \left(\frac{x}{\Delta t}\right)^{2}\left(\rho_{web} + \frac{2\,\rho_{air}}{2\,\pi\, f_{web}\sqrt{\left(\frac{\Delta t}{x}\right)^{2} - \left(\frac{1}{C_{air}}\right)^{2}}}\right) \tag{2}$$

where x is the system microphone spacing and C_{air} is the speed of sound in air.

Through experimentation and evaluation, both in field and laboratory settings, signal conditioning and signal processing schemes were developed so as to enhance results achieved through equation (2). Sensitivity analysis of equation (2) revealed that variation in the time of flight value had great influence on tension indications. Additionally, this analysis revealed that characteristic frequency variation, if neglected, was sufficient to create excessive tension measurement error. Experimental approach thus became one where time of flight Δt would be computed as precisely as possible whereas characteristic frequency f_{web} would be computed so as to provide adequate resolution about some nominal characteristic frequency value.

Cross correlation techniques were used to compute time of flight values. Equation (3) is the basic cross correlation relation which was applied, where sequences x_n and y_n correspond to acquired computer data records from the upstream and downstream system microphones, respectively, and T_s is the sample period. Typical time of flight values for web materials and web tension levels examined in this study were in the one millisecond range. Sampling rates of 200 to 300 kHertz per channel used in data acquisition allowed for 5.0 to 3.3 microsecond resolution, respectively. Time of flight was determined through cross correlation record scanning, where $\Delta t = r\,T_s$ at the point where maximum correlation existed. If uncertainty in this selection was estimated as +/- one sample shift, then uncertainty in Δt was +/- 2.5% to +/- 1.7% for an assumed one millisecond Δt value, using sample rates described above respectively. Web flexural waveform speed was typically such that a two millisecond window was available for data capture. With the above sample rates in use, 400 to 600 data samples were available per channel for cross correlation processing. Time of flight values derived in this manner compared very well to oscilloscope waveform traces and performance remained predictable and repeatable under severe industrial conditions. Signal conditioning applied prior to this process did not affect time of flight results.

$$\widehat{R_{xy}}(rT_s) = \frac{1}{N - r} \sum_{n=1}^{N-r} x_n \; y_{n+r} \quad ; r = 0, 1, 2, \ldots, m \tag{3}$$

Fourier transform techniques were used to derive the flexural waveform characteristic frequency. Equation (4) is the discrete Fourier transform relation for a periodic sequence $\tilde{x}(n)$, the tilde indicating periodicity. Transformed sequence $\tilde{X}(k)$ is also periodic in period $\omega = 2\pi$ and symmetric about the midspan $k=N/2$ or $\omega=\pi$. Additionally, for a periodic sequence $\tilde{x}(n)$ the transformed magnitude sequence $|\tilde{X}(k)|$ will be discrete in that frequency components comprising $\tilde{x}(n)$ will be represented by spikes of varying amplitude on the frequency axis k. A characteristic frequency could then be determined by frequency domain spike magnitude comparisons.

$$\tilde{X}(k) = \sum_{n=0}^{N-1} \tilde{x}(n) \;\; \exp[-j\, 2\pi kn/N] \tag{4}$$

Computing f_{web} proved to be a challenging task due to flexural waveform signal nature, sampling concerns, and required frequency domain resolution. Earlier discussion reported that the generated web flexural waveform signals had characteristic frequency of approximately 1200 to 2500 Hz from viewing oscilloscope traces. Also mentioned was that roughly a two millisecond window existed to acquire all of the relevant signal information. To be described below are the tradeoffs that were used to optimize this resultant f_{web} computation.

With respect to cross correlation data acquisition, sample rates of 200 to 300 kHertz per channel were used to achieve adequate time domain resolution. From a frequency domain perspective, these sample rates imply that the signal bandwidth in question was in the 100 to 150 kHertz range. For a 1024 point Fourier transform, frequency domain resolution (Δf) would be 97.6 to 146.4 Hertz, respectively. If the signal characteristic frequency was in the 1200 to 2500 Hz range, then only a few increments of Δf would span this entire bandwidth. Thus, to increase frequency domain resolution sampling rate had to be lowered substantially.

An examination of sampling rates with respect to signal bandwidth was in order. If signal bandwidth was assumed limited to 5000 Hertz to cover all likely web material and tension possibilities, then Nyquist sampling theorem suggests a 10 kHz per channel data sampling rate. Using a 512 point Fourier transform with this sample rate would provide frequency domain resolution of 19.5 Hertz, which would be quite adequate. Drawback here was that all relevant signal information occurred in a two millisecond span such that only 20 data points could be acquired using this sample rate. Thus, optimal frequency domain resolution could only be achieved through acquisition of many signal records in order to construct a long enough data record for Fourier transform processing.

Solution to these problems was accomplished through a sampling versus frequency domain resolution tradeoff. Indicated earlier, desired was knowledge of a nominal characteristic frequency and any perturbation about this nominal value. This implied that good frequency domain resolution be maintained. A compromise in sampling rates was made to speed the overall sampling process.

Equation (4) was the discrete Fourier transform relation for a periodic sequence. Signals acquired through this web tension measurement system were transient in nature. Individual sample records $x(n)$ were acquired and placed front to back in a resultant pseudoperiodic data record $\tilde{x}(n)$ that approximates the following relation (5):

$$\tilde{x}(n) = \sum_{r=-\infty}^{\infty} x(n+rM) = x(n \text{ modulo } M) \tag{5}$$

Here, the transformed record $\tilde{X}(k)$ will appear equivalent to that from a periodic sequence. As was indicated earlier, characteristic frequency f_{web} could then be selected through magnitude sequence viewing. Sample rates of 25 to 30 kHertz per channel were used, which resulted in 50 to 60 data samples per pneumatic system pulse (cycle). Sampling was performed for sufficient cycles such that a 512 point data record was filled. Zero packing was used such that this 512 point data record was appended with 512 zeros. This technique served to double frequency domain resolution. For sample rates of 25 to 30 kHertz, resolution Δf equaled 24.4 to 29.3 Hertz, respectively. This approach provided needed frequency domain resolution while supplying signal averaging through multi cycle record construction.

Prior to Δt and f_{web} computation, bandpass filtering was applied to the raw data records. Referring to Figure 3, bandpass filtering would attenuate high frequency noise from the pneumatic shock pulse and eliminate low frequency web flutter present after web flexural waveform passage. Originally performed by analog means, this filtering was converted to a digital algorithm. Bandpass filter gain, center frequency, and bandwidth were then user specified and could be varied so as to adapt filtering to the web tension situation at hand. Best tension results have been achieved through "tuning" of the measurement system to the signals being sensed. This tuning involved filter center frequency positioning near the actual waveform characteristic frequency while expanding/contracting the filter bandwidth such that characteristic frequency perturbations would not be adversely affected.

No tension measurement system calibration was required prior to use. Web area density and web transport velocity were the only physical parameters requiring entry before beginning a test. Figure 4 is an example of an initial web waveform trace with default digital filtering parameters in use. At this point the trace position could be adjusted as could filter parameters and sample rates as indicated in the figure. When satisfied with system tuning, the user could then proceed with a tension measurement test. Single and multi point tension test programs were developed for the system. Single point testing allowed for viewing of the signal processing results such that additional system fine tuning could be performed. Multi point testing could be used to obtain tension profiles across a web span, with a graphical tension summary made available at test conclusion.

EXPERIMENTAL RESULTS

To illustrate the tension system in use, some results will be presented below. A single point test will be outlined, where 2 mil NOMEX material with 126.4 N/m (0.72 pli) average tension was tested in the laboratory. Figure 5a is a raw (unfiltered) oscilloscope trace where Figure 5b is the corresponding filtered trace using filter center frequency 2000 Hertz and bandwidth 2500 Hertz. Sampling rate used was 400 kHertz, or 200 kHertz per channel. Cross correlation function from the two filtered microphone signals is provided in Figure 6. Index corresponding to maximum cross correlation value multiplied times the sample period resulted in a 0.915 millisecond time of flight value. Figure 7 is the frequency magnitude spectrum, achieved through Fourier transform of an assembled pseudoperiodic record from upstream microphone signals. Maximum spectral peak index multiplied times the frequency increment Δf resulted in a 2514 Hertz characteristic frequency value. Substitution of these results and the web area density into equation (2) resulted in a tension indication of 152.8 N/m (0.870 pli). Since tension will likely vary across a web span, tension from such a single point test will likely be different from the average applied tension. A tension profile should be used to best judge system accuracy.

As was indicated earlier, field testing was performed during tension measurement system development. Below are results from such a test conducted at a polypropylene web manufacturing plant. Plastic web material of thickness 0.5 to 1.5 mil thick is produced at this facility typically in 10 foot wide web spans at tension levels 35 to 140 N/m (0.2 to 0.8 pli) with transport velocities 120 to 150 meters per minute (400 to 500 ft/min). Inherent problems such as bowed rollers, electrostatic coating facilities, general noise, and machine eccentricities were present during these trials. Figure 8 is a graphical summary for a tension profile test for 1.1 mil thick plastic web at nominal, average tension of approximately 123 N/m (0.7 pli). Nominal tension variation was due to said machine/roll eccentricities. The average tension indicated in Figure 8, 0.718 pli (126.1 N/m), is quite consistent with the nominal tension value. Tension profiles for this type of web material are typically somewhat U shaped, which is reflected in the graphical summary.

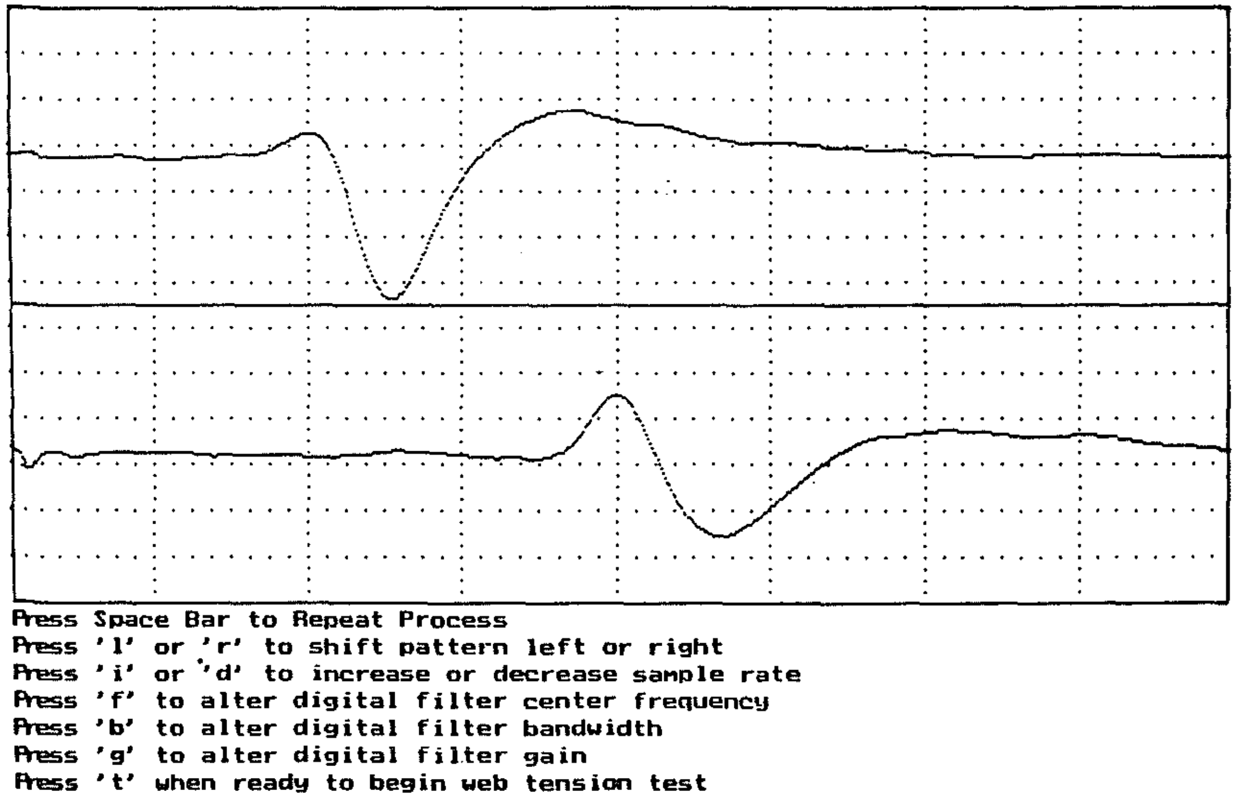

Figure 4. Display of waveform with initial digital filter parameters in use.

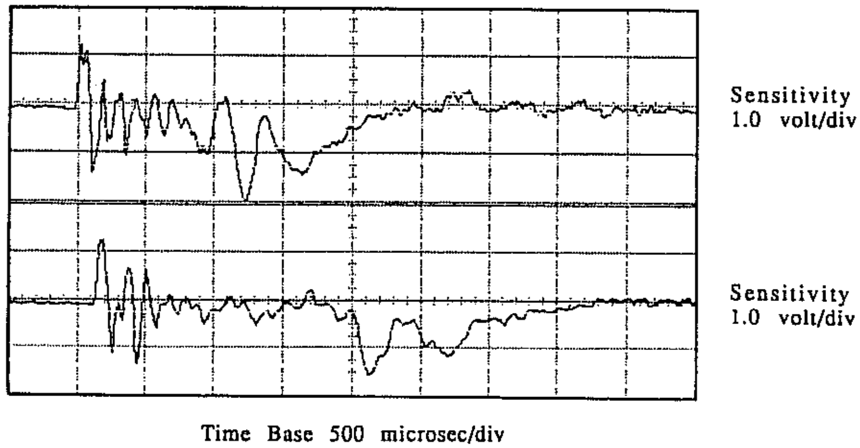

Figure 5a. Raw unfiltered signals from 2 mil NOMEX web material.

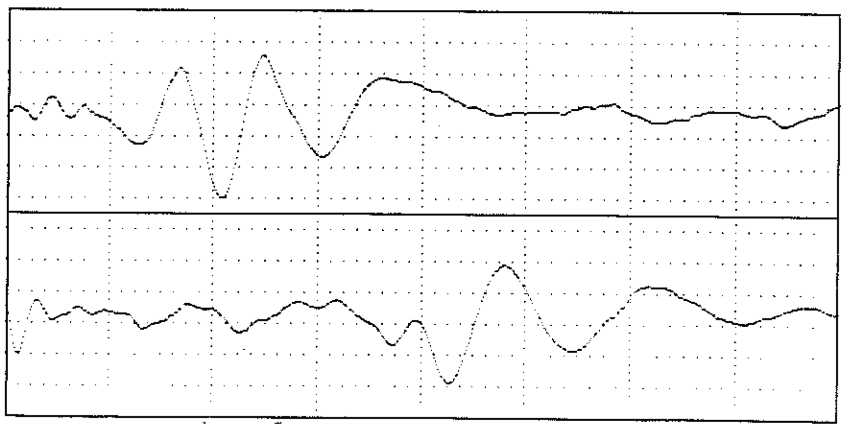

Figure 5b. Resultant 2 mil NOMEX signals after filtering.

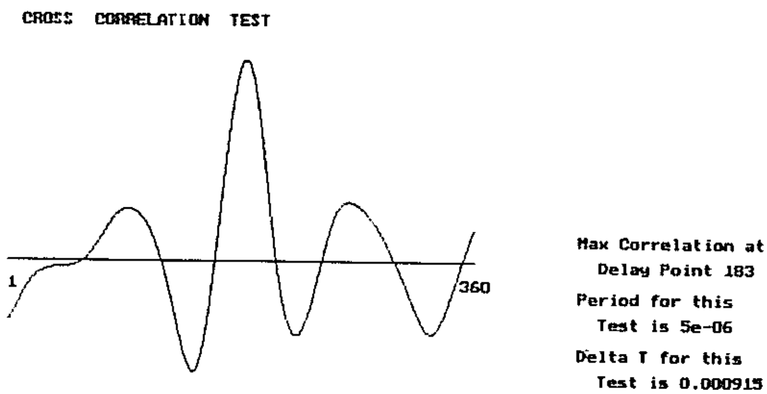

Figure 6. Cross correlation function for the signals of Figure 5b.

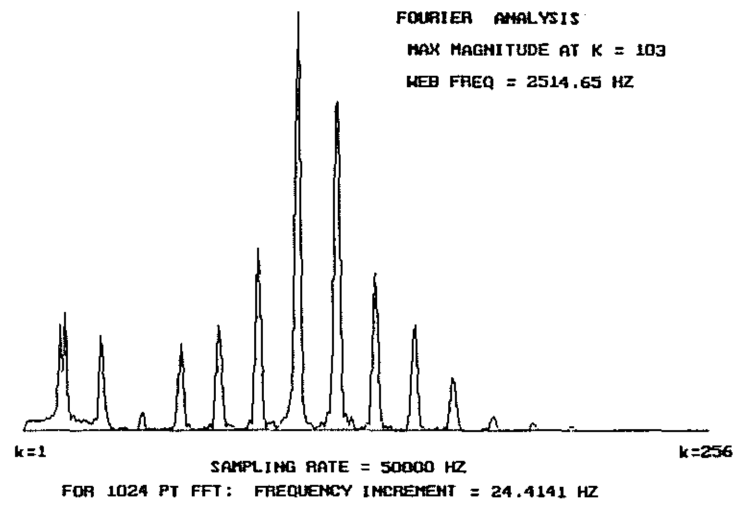

Figure 7. Spectral density function from pseudoperiodic signal record.

CONCLUSION

Presented above have been practical aspects of a new local tension measurement system developed for the web producing/handling industries. Knowledge of web tension is basic for accurate and uniform web production control and subsequent roll and product quality. Objective of this research was a small, inexpensive, noncontacting tension measurement system that could be adapted to a broad range of web materials and tension levels. A short presentation of the developed methodology was provided, where a pneumatic weak shock pulse was coupled to a web under test. This coupling proved to be less complete than expected so that signal conditioning and signal processing was used to enhance tension measurement results. Examples of a laboratory point tension test and an industrial tension profile test were used for illustration. This system has shown good performance in a variety of tension measurement situations. Variable pulse rate and system tuning facility allows for a customized response depending on web material and nominal web tension. Compact transducer head lends itself to close quartered industrial applications without influencing generated flexural waveforms. The system requires no calibration; system accuracy may be judged through comparisons of average tension via winder load cells and average tension results computed through tension profile tests. It is believed that this tension measurement system may be easily implemented in a variety of web handling or web processing facilities with good, repeatable results being achievable.

[1] Meinander, S., and Marttinen, T. "Measuring Web Tension Using Contactless Tension Meter." Technical Research Center of Finland. *Graphic Arts Laboratory*, Vol. 11, No. 1 (1983), pp. 34-36.

[2] Rye, T. W. "Using Tenscan to Measure the Tension Profile." *1988 Tappi Finishing and Converting Conference Proceedings*, pp. 175-178.

[3] Morse, P. M., and Feshbach, H. *Methods of Theoretical Physics*. New York: McGraw-Hill Book Co., 1953.

[4] Merilainen, P. "Propagation and Excitation of Membrane Waves Loaded by Air." *Microwaves, Optics, and Acoustics*, Vol. 2, No. 5 (Sept. 1978), pp. 147-152.

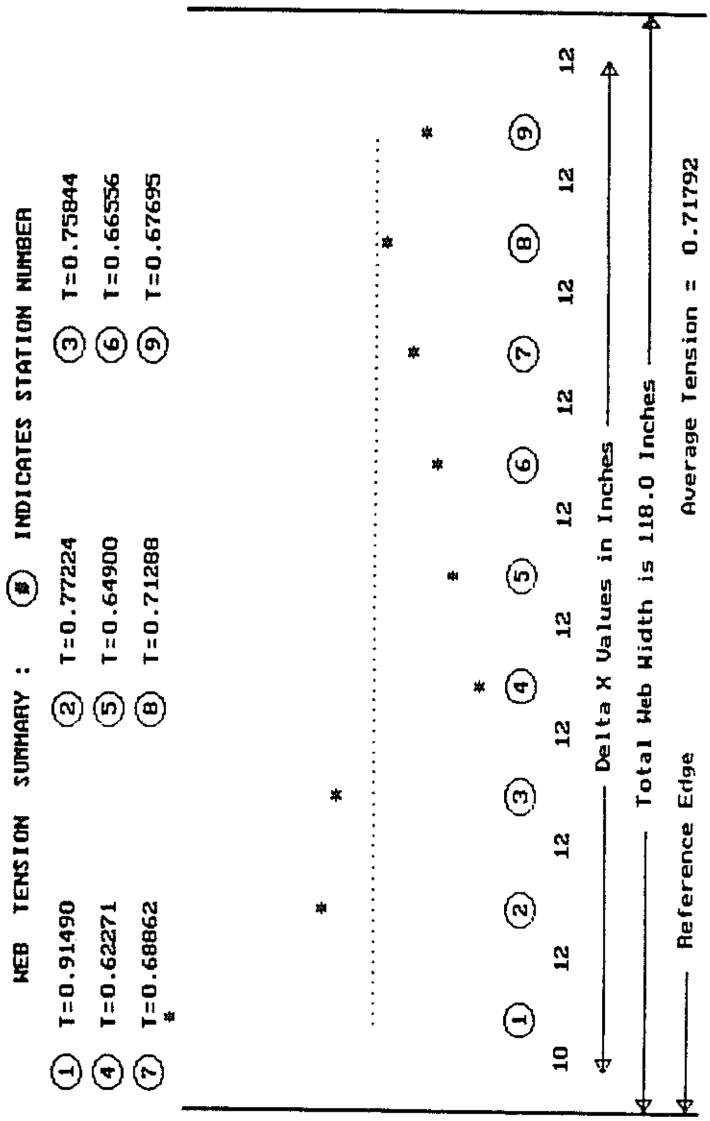

Figure 8. Tension profile from industrial polypropylene web line.

QUESTIONS AND ANSWERS

Q. Could your tension measurement system be used to provide feedback information in an on-line tension control situation??

A. I would suppose so, if you had it set up where you were very confident. That is, if you used it over time and tested it under all the conditions and it was repeatable. The system has been fairly repeatable, but we haven't done any long term studies, so I can't really answer that regarding long term effects. There are some mechanical components that may degrade over time. Some of the consortion members have, I believe, developed their own systems and could answer that a little bit better for you than I could. But, I think the numbers, the indications that the system provides are of sufficient quality that you could certainly use them in that context.

Q. What kind of success have you achieved with your system in measuring tension on materials of higher basis weight (higher area density (Kg/m^2))?

A. We've tested this system out on a variety of materials, had good success up to 3 mil material, such as floppy disk material, which is fairly stiff, and some 3 mil plastic, we have had good success with that. NOMEX (DuPont trademark) up to 10 mils thick, we've tested this out on. Some of the thicker, stiffer material, if it has a slick surface on it, is harder to test, because it's harder to bend; the driver has very good capability, but even it has its limits. So, to keep the system non-contacting, if that is very critical, you can probably not test quite as thick and as tightly wound material, because you probably need to keep the apparatus away from your material. If you don't mind touching it, of course, then you could perhaps achieve good performance out of some stiffer materials.

Q. In your tension equation (2), is tension proportional to web material mass density??

A. Yes, there is a units conversion in there that I left out (converting Kg/sec^2 to N/m).

Q. Some German researchers, Habager and Baum, have generated traveling waveforms on webs through ultrasonic means, resulting in materials property information. Are you familiar with this work and how are your system waveforms different from theirs?

A. Yes, sir. Well, these are out of plane waves for one thing, unlike Lamb waves, these are flexual in nature. I don't believe we're talking about the same thing; there are two different types of waves being compared here.

Q. Do your waveforms propagate in all directions from the source such as ultrasonic method waveforms travel?

A. These wave forms are traveling, following the direction of tension. They will not propagate transversely. For example, you must align the system transducer head parallel to the web. If you start rotating the transducer head away from parallel more than 30 degrees, it will no longer work properly. So, the generated waveform follows a very narrow path through the web span. Is that any explanation at all? The system is non-contacting, also, which ultrasonic systems typically are not.

Q. In order to obtain web material Young's Modulus in various directions, transverse waveform propagation is required. Polar plots of Young's Modulus versus propagation angle may be then produced. How do you accomplish this with your system?

A. Well, we're not trying to find Young's modulus here. We are not looking for material properties, rather, our objective is measuring tension.

Q. Could your system be configured with multiple transducer heads; your system at present utilizes one transducer head, is that correct?

A. Yes, that has been our approach. If you desired a system that had multiple heads, you could experiment with that. You would have to drive each transducer head. We are in the idea business, we are not in that part of it, the development business beyond system prove in.

Q. Are all of your measurements acquired at once or is there some delay for system positioning prior to measurement?

A. Well, the system progresses from one side of a web to the other, but it is not instantaneous, data acquisition is not done all at one time. Yes, there is a regular traverse that we use to move the transducer head across the web.

Q. How fast can your system move through a set of measurements? What kind of repetition rate can you achieve?

A. You are asking how fast we may cycle the pulsar, I think. Is that correct?

Q. What is the limiting factor on system speed? Is it data acquisition, signal processing, positioning, etc.? Couldn't your signal processing work be performed while the traverse is being repositioned, for example?

A. Well, that gets into fine tuning things. One may use DSP boards or whatever is desired to accomplish signal processing aspects. The system throughput limit is how fast one can pulse the web under test.

Q. Is not system speed dependent on flexural waveform travel on the web? Couldn't you begin data acquisition when a pulse is initiated?

A. Well, the pressure pulse must propagate along the length of the tube, and there are mechanical aspects there that can not act instantaneously, such as pressure pulse gating. These are somewhat of a limiting factor. Now, maybe some of the consortia members have ironed out some of these problems and can make the system work faster.

Q. How fast can you pulse a web with your pneumatic pulser?

A. Around 30 pulses per second, if you really wanted to wrap it out, but I question how long some of the components would last if you ran it that fast for very long. I typically sample at 4 Hertz (4 pulses/second), perhaps.