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Monitoring the Mechanical Behavior of Paper During Papermaking

P.H. Brodeur, J.P. Gerhardstein, E.F. Lafond, J.H. Jong, C.C. Habeger,
B.M. Pufahl, V.A. Deason, K.L. Telschow, Y.H. Berthelot

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INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
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- to provide a multidisciplinary education to students who advance the science and technology of the industry and who rise into leadership positions within the industry;
- to conduct and foster research that creates knowledge to satisfy the technological needs of the industry;
- to serve as a key global resource for the acquisition, assessment, and dissemination of industry information, providing critically important information to decision-makers at all levels of the industry; and
- to aggressively seek out technological opportunities and facilitate the transfer and implementation of those technologies in collaboration with industry partners.

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MONITORING THE MECHANICAL BEHAVIOR OF PAPER DURING PAPERMAKING

Pierre H. Brodeur, Associate Professor
Joseph P. Gerhardstein, Associate Engineer
Emmanuel F. Lafond, Associate Scientist
Jimmy H. Jong, Assistant Scientist
Charles C. Habeger, Professor
Brian M. Pufahl, Assistant Engineer
Institute of Paper Science and Technology
500 10th St., N.W.
Atlanta, GA 30318

Vance A. Deason, Senior Scientist
Kenneth L. Telschow, Senior Scientist
Idaho National Engineering and Environment Laboratory
Lockheed Martin Idaho Technologies
P.O. Box 1625
Idaho Falls, ID 83415-2209

Yves H. Berthelot, Professor
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

ABSTRACT

Monitoring the mechanical behavior of paper during papermaking has long been sought after for one main reason: it would enable real-time control of the papermaking process. Implications of this achievement are substantial: optimized use of raw materials, reduction of operating costs, energy savings, and performance optimization of paper products. We report in this paper a research program aimed at providing the missing measurement and data interpretation tools to support the future development of real-time process control strategies during papermaking. The program has two major objectives: 1) develop and field test the necessary hardware to gather on-machine information on the mechanical behavior of paper; 2) use this information along with already existing information such as grammage and moisture content to begin an investigation of the inverse problem of predicting papermaking process conditions from measurements. The rationale for real-time monitoring of paper stiffness is first introduced. Then, the concept of simultaneous detection of stiffness orientation distribution (SOD) and fiber orientation distribution (FOD) to extract the contribution of built-in stresses to the overall sheet stiffness is presented. An overview of the research program is next reported. Finally, the demonstration of stiffness measurements on moving paper at production speeds using a noncontact laser ultrasonics method is briefly reviewed.

INTRODUCTION

Several studies have shown the dependency of elastic stiffness properties upon paper machine process variables [1-6]. Table I illustrates the effect of process changes on these properties. Increasing the refining and/or wet pressing levels increases longitudinal stiffnesses [C_{11}, C_{22}, and C_{33}] and shear stiffnesses [C_{44}, C_{55}, and C_{66}] (see Ref. 7 for a description of paper elastic stiffness constants). C_{11} and C_{22} are sensitive to an increase in fiber orientation (MD-CD anisotropy), but C_{33} is not. As another example, increasing the wet straining level along machine direction increases C_{11}, but decreases C_{22} and C_{33}. These findings support the idea first proposed by Baum in 1987 [3] that the measurement of paper elastic stiffness properties could serve as the basis for real-time control of the papermaking process and, hence, could be used to optimize the end-use performance of paper products.

Table I. Effect of process variables on elastic stiffness properties.

Elastic Stiffness Constants	Refining Level	Fiber Orientation	Wet Pressing Level	MD Wet Straining Level	Restrained Drying	Calendering
	Increasing	*Increasing*	*Increasing*	*Increasing*	*From Full to MD Only*	*Increasing*
MD: C_{11}	↑	↑	↑	↑	0	↓
CD: C_{22}	↑	↓	↑	↓	↓	↓
ZD: C_{33}	↑	0	↑	↓ (large)	↑ (small)	↓
MD-CD: C_{66}	↑	↓	↑	0	n.a.	↓
MD-ZD: C_{55}	↑	↑ (small)	↑	↓ (small)	n.a.	↓
CD-ZD: C_{44}	↑	↓	↑	↓	n.a.	↓

While the effects of process conditions on stiffnesses are relatively well established from a qualitative stand-point, grade-specific measurements are lacking and the inverse problem of predicting process changes from measurements has received very little attention [8]. The desire to move ahead with the complex task of investigating the inverse problem and, hence, provide the necessary background information to support the development of real-time control strategies, triggered an important research program at the Institute of Paper Science and Technology.

One must reemphasize here that the motivation for monitoring paper stiffnesses is to use these parameters for process control. Whether or not these properties correlate to tensile strength, short-span compression or any other parameter regularly obtained in the mill laboratory for long-term quality control is not a relevant issue. On-machine stiffness measurements must stand by themselves, and the challenge is to determine how they can best be used to control a paper machine and optimize the end-use performance of paper products. For example, one could envision optimizing strength properties of board materials through stiffness optimization of the moving web, which means that the grammage could be allowed to fluctuate and/or less furnish would be needed to meet strength objectives.

ON-MACHINE MONITORING OF PAPER MECHANICAL BEHAVIOR

Limitations of Stiffness Measurements

As appealing as the idea put forward by Baum can be, on-machine monitoring of stiffness properties may be insufficient because different process changes (e.g., increase in refining, fiber orientation, wet pressing, or wet straining) can have similar effects on a single property. This is certainly the case for C_{11} (see Table I). Also, a single process change can affect in a similar manner different stiffnesses as verified by an increase in refining, which contributes to an increase of all stiffnesses. In other words, it does not appear possible to have a sufficient number of independent stiffnesses to match the number of process variables. This prescribes the need for additional information. This information may certainly include fiber morphology parameters such as fiber length and fiber curl and other variables commonly monitored on a paper machine such as grammage, thickness, and moisture content. However, this may still be insufficient. As introduced in the next section, it is hypothesized that the measurement of built-in stresses may significantly enhance the level of required information.

Determination of Built-in Stresses

Assuming that the "geometrical" fiber orientation distribution (FOD) and stiffness orientation distribution (SOD) in the plane of paper can be measured in a simultaneous manner using appropriate test methods (see below), additional information about the contribution of built-in stresses to the overall sheet stiffness can be determined. The FOD must not be confused with the fiber orientation angle, which corresponds to the degree of fiber misalignment with respect to machine direction [9]. Similarly, the SOD is different from the stiffness orientation angle, which refers to the angle of maximum stiffness with respect to MD [9]. Providing that the FOD and SOD are determined, fiber and stiffness orientation angles are de facto available.

The concept of decoupling FOD and SOD for the purpose of extracting the contribution of built-in stresses was explored by Haynes [10]. Results from a study by Ishisaki [6] about a comparative analysis of FOD and SOD can be used to explain how the simultaneous detection of these distributions can be useful. In this work, several constant grammage sheets (80 g/m^2) were prepared under different process conditions using a laboratory dynamic sheet former. A small percentage of dyed fibers was added to the bleached kraft furnish to determine the fiber orientation distribution using an automated image analysis technique [9]. Also, all sheets were tested using an ultrasonic contact method to probe the stiffness orientation distribution [11]. Figure 1 displays a series of fiber orientation distributions for sheets subjected to different process conditions: with and without wet straining and with full (MD-CD) or MD restrained drying. Respective stiffness orientation distributions for these sheets are shown in Figure 2. The MD/CD stiffness ratio and simulated fiber orientation (misalignment) angle with respect to machine direction for the control sheet (no straining, MD-CD restrained drying) are 2.1 and 15 degrees, respectively. It is observed that wet straining and/or MD restrained drying do not significantly affect the FOD. However, the situation is very different for the SOD: as expected, wet straining increases stiffness along machine direction (elongation effect) and MD restrained drying diminishes stiffness along cross-machine direction (shrinkage effect). These effects are consequences of the development of built-in stresses during restrained drying. Ishisaki's results support the hypothesis that FOD is not significantly sensitive to built-in stresses, thus providing a basis to extract the contribution of built-in stresses to the overall stiffness. The lower right distribution in Figure 2 (wet straining + MD restrained drying) illustrates the complexity of using stiffnesses to evaluate process conditions.

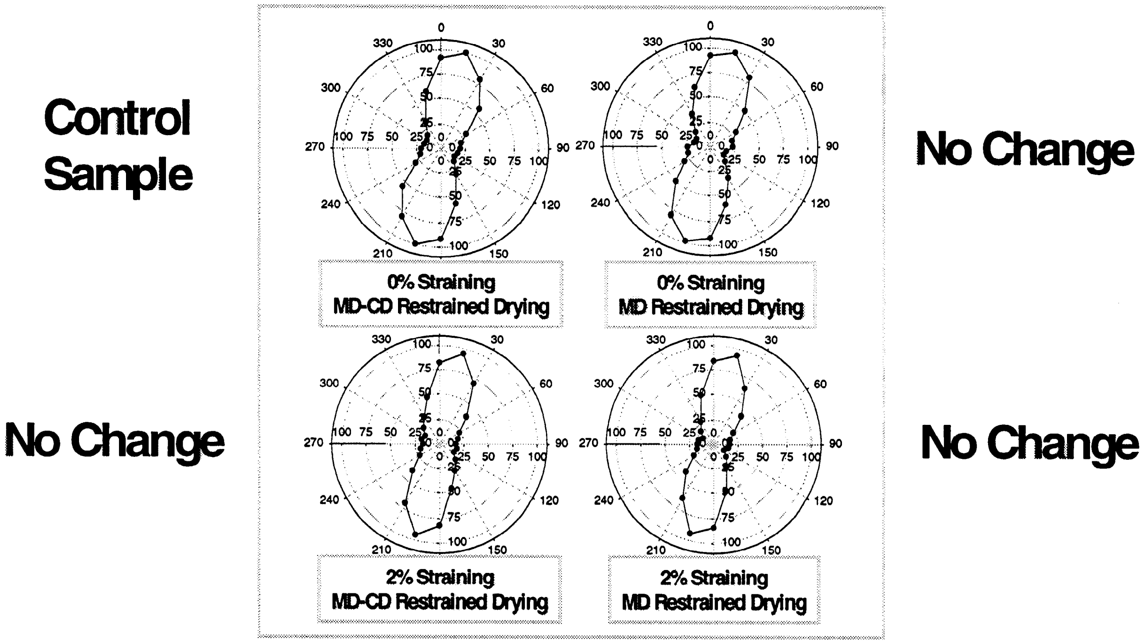


Figure 1. Fiber Orientation Distribution (FOD) for paper samples prepared under different wet straining and restrained drying conditions using a laboratory dynamic sheet former. The control sample (MD/CD ultrasonic stiffness ratio of 2.1 and simulated fiber misalignment of 15 degrees) is in the upper left corner. Wet straining and MD restrained drying conditions do not appreciably affect the FOD.

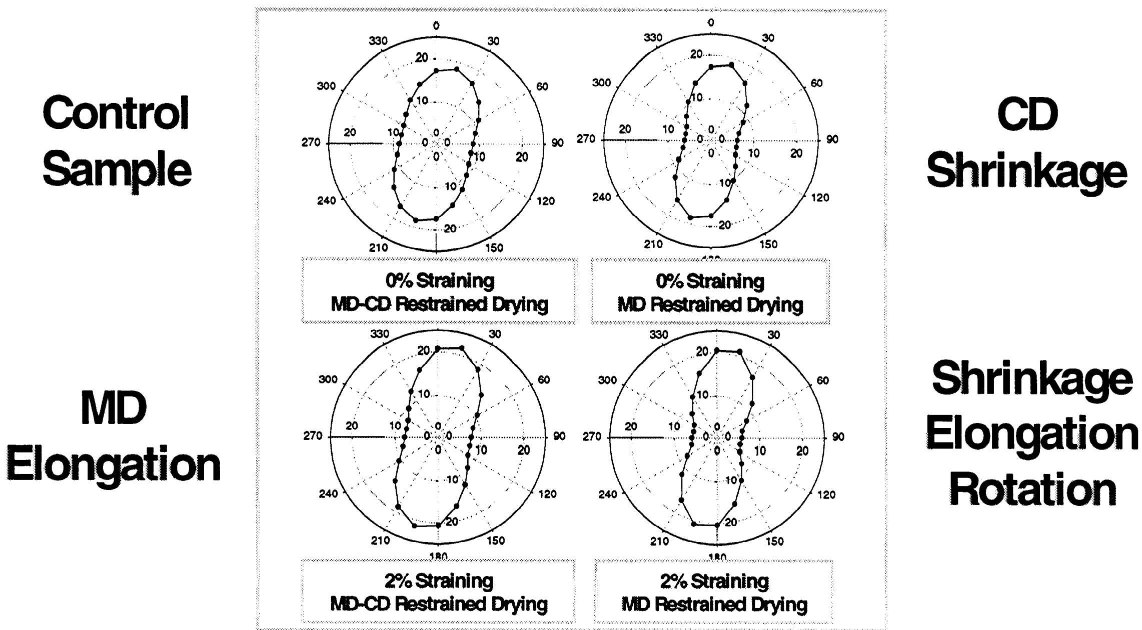


Figure 2. Stiffness Orientation Distribution (SOD) obtained for paper samples prepared under different wet straining and restrained drying conditions. To facilitate comparison, results shown in this figure were obtained using the same sheets as Figure 1. Wet straining and MD restrained drying affect SOD.

RESEARCH PROGRAM

The development of on-machine instrumentation to monitor paper stiffness has been an on-going activity for several years. Most research efforts have focused on implementing ultrasonic contact methods to test board grades [12-15]. More recently, research work was undertaken to investigate noncontact laser ultrasonics principles to probe stiffness properties [16]. Providing that the use of lasers to excite and detect ultrasonic waves does not damage the moving web, merits of laser ultrasonics are important: unique potential to test a wide range of grades, including tissues, paper grades, board grades, and coated grades; rich information content (simultaneous detection of in-plane and out-of-plane stiffnesses); simultaneous detection of SOD and FOD; potential for 100% web inspection implementation. Exploratory measurements obtained on non moving paper samples have shown a strong correlation between contact and laser-based measurements for different grades from newsprint to 69-lb linerboard [16].

Success in the initial laser ultrasonics exploratory study led to the granting of funding in 1997 to demonstrate the feasibility of applying the laser ultrasonics technology to a moving web, first in the laboratory using a moving web simulator, and then, in a mill setting using a prototype on-machine instrument [17]. Considering the unique attributes of a paper web (to name a few: rough and poorly reflective surface, fluttering, moving speeds in the 50-100 km/h range) and harsh testing conditions in a mill environment, the challenge is tremendous. In order to ensure success, a multi-disciplinary research team composed of researchers from the Institute of Paper Science and Technology, Idaho National Engineering and Environment Laboratory, and Georgia Institute of Technology was assembled. From the early days, it was determined preferable to first implement a single-point detection system mounted on a scanning platform rather than embracing the more appealing concept of 100% web inspection using an array of static sensors mounted across the web. The reasoning behind this strategy was to begin mill trials as quickly as possible for the purpose of generating grade-specific databases on process changes vs. measurements. Then, more advanced technology suitable for 100% web inspection would follow. Up-front specifications for the prototype on-machine instrument include the detection of symmetric and asymmetric modes of Lamb waves (see below) along machine and cross-machine directions to gather as many in-plane and out-of-plane stiffness properties as possible, the measurement of SOD using either symmetric or asymmetric waves propagating in several directions with respect to machine direction, and the determination of FOD using an integrated light scattering method.

A summary account of the demonstration of laser ultrasonics measurements on moving paper is presented in the next section. The determination of FOD is now briefly described. The use of light scattering to probe the fiber orientation (misalignment) angle is not new [18]. The more difficult task of using scattered light to infer FOD indirectly has been investigated on non moving paper only [6, 19]. Hence, it was deemed necessary to revisit the measurement approach to determine FOD on a moving web and verify that the distribution is insensitive to built-in stresses [15]. An experimental light scattering apparatus was devised [6, 17]. Also, an automated image analysis system was developed to obtain direct (reference) FOD measurements on laboratory oriented sheets containing a small percentage of dyed fibers, and calibrate light scattering measurements [17].

Finally, a directed paper physics research effort was initiated in parallel to hardware development. It consists of four subtasks: development of analytical tools to extract stiffness properties from Lamb wave measurements [20, 21], investigation of moisture and temperature effects on stiffnesses using a special laser ultrasonics setup and a moisture/temperature controlled cabinet [17], development of a method to decouple FOD and SOD, and development of a semi-empirical predictive model of process changes. In the latter case, it was decided to orient the research work on copy paper because laser ultrasonics offers unique measurement capabilities for this particular grade, including the measurement of bending stiffness. The experimental methodology involves the analysis of a comprehensive set of laboratory oriented sheets prepared under different process conditions and tested using readily available laboratory equipment. The goal is to develop a preliminary version of the predictive model in time to be tested in conjunction with the prototype instrument during mill trials. It should be stressed that the development of a reliable and useful predictive model is a long-term goal exceeding the scope of the research program.

The mill demonstration of the prototype on-machine instrument and the availability of a preliminary version of the predictive model relating measurements to process changes constitute the main deliverables of the research program.

LASER ULTRASONICS MEASUREMENTS ON MOVING PAPER

The experimental demonstration of noncontact laser ultrasonics measurements on moving paper is summarized [22]. Two types of Lamb waves can be generated using a laser beam focused on the surface of paper: symmetric or S waves and asymmetric (bending) or A waves. Figure 3 displays the general shape of the fundamental S_0 and A_0 modes for symmetric and asymmetric Lamb waves, respectively. Lamb waves are dispersive, which means that the phase velocity is frequency dependent. Typical dispersion curves for Lamb waves propagating in the machine direction are shown in Figure 4 for copy paper. One can see that the S_0 mode is sensitive to three stiffnesses, of which C_{11} (MD longitudinal stiffness) and C_{33} (ZD longitudinal stiffness) are of particular interest (see Table I). Similarly, the A_0 mode is sensitive to C_{11} and C_{55} (MD-ZD shear stiffness).

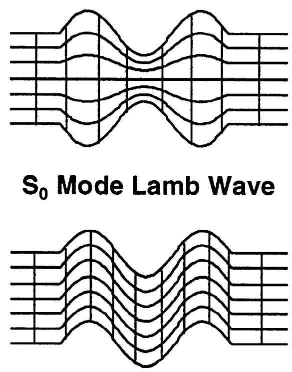


Figure 3. Fundamental S_0 and A_0 modes for Lamb waves.

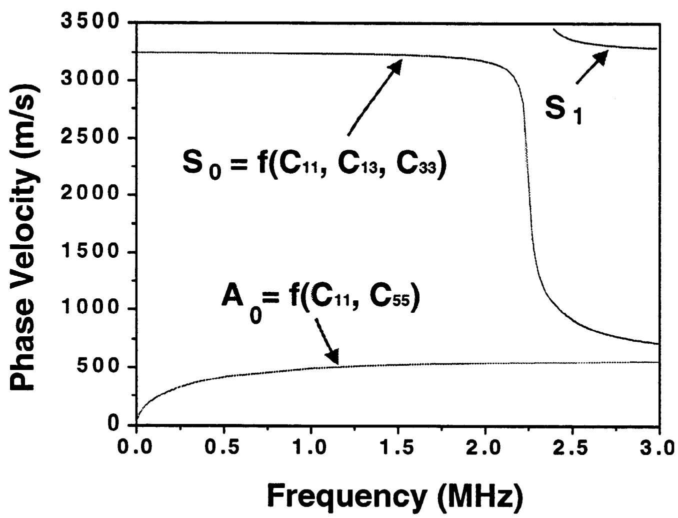


Figure 4. Dispersion curves for Lamb waves propagating in the machine direction for copy paper.

Five different laser ultrasonics detection techniques received initial consideration in the quest to determine a likely successful method for an on-machine implementation. One of them, the so-called Photoinduced-EMF detection method was capable of detecting Lamb waves at record-breaking web speeds [23]. Measurements were performed using a specially designed variable-speed/fluttering web simulator capable of speeds exceeding modern paper machine production speeds [24]. Figure 5 illustrates a schematic diagram of the Photoinduced-EMF detection scheme. On the left side of this figure, one can see the position of the web simulator. A photograph of the experimental setup is shown in Figure 6. A Nd:YAG pulsed laser operating at 1064 nm was used to generate Lamb waves in a near thermoelastic regime. A CW Ar:ion laser was used for detection. Typical measurements are reported in Figure 7 for copy paper and 42-lb linerboard. These results are very promising and demonstrate that laser ultrasonics principles can be successfully applied to moving paper. An analysis of copy paper results, including a comparison with contact ultrasonics measurements, can be found in Ref. 22.

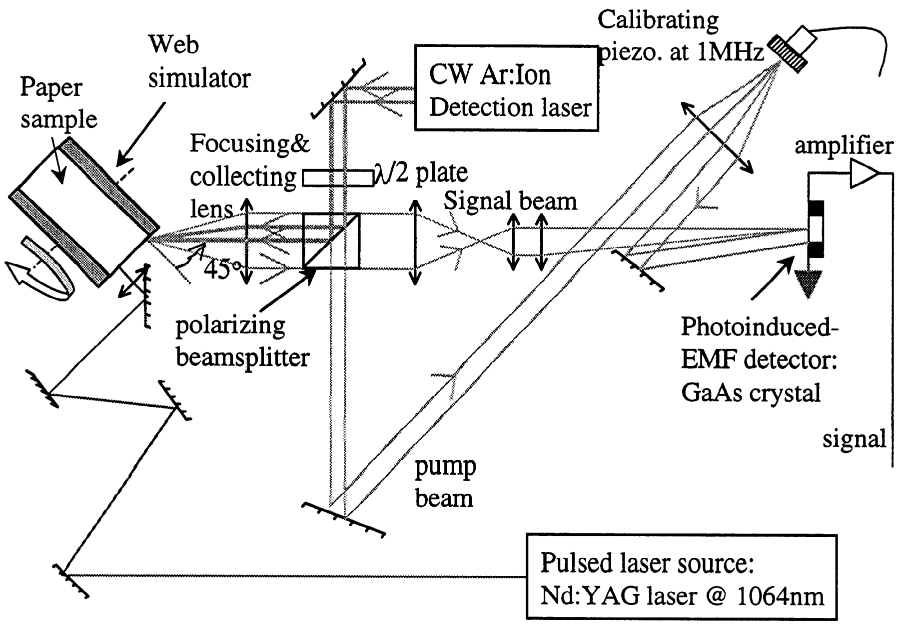


Figure 5. Schematic diagram of the laser ultrasonics system for excitation and detection of ultrasonic waves in paper. A pulsed Nd:YAG laser operating at 1064 nm was used for wave excitation. A CW Ar:ion laser and a Photoinduced EMFdetection system were used for wave detection.

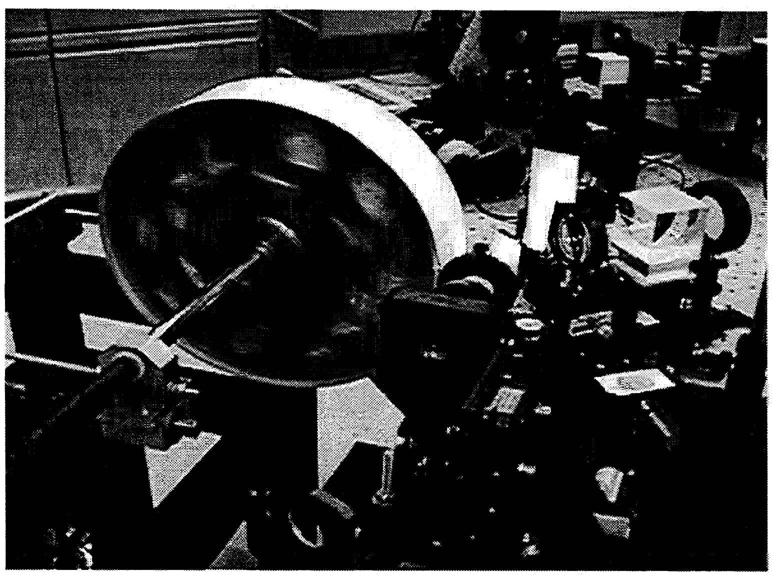
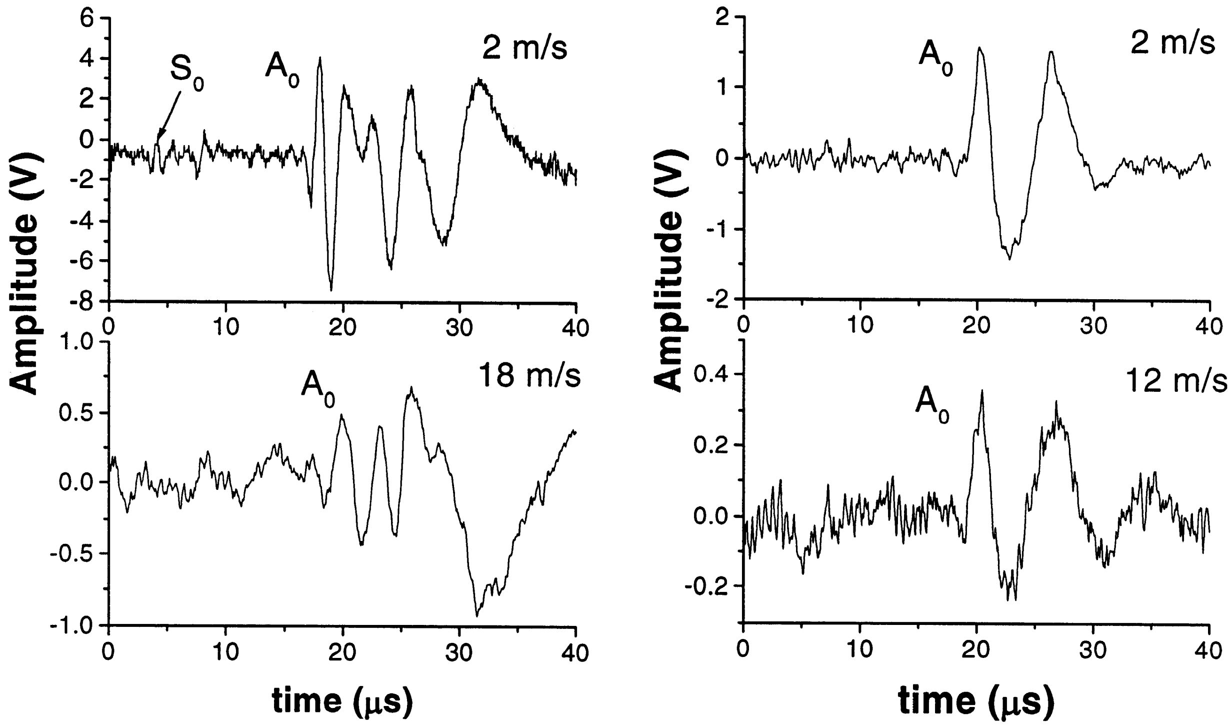


Figure 6. Photograph of the experimental setup for the demonstration of the laser ultrasonics technology on moving paper.



(a) Copy paper in MD

(b) 42-lb linerboard in MD

Figure 7. Typical Lamb wave signals obtained on (a) copy paper at 2 m/s and 18 ms/s (production speed) and (b) 42-lb linerboard at 2 m/s and 12 m/s (production speed). The S_0 mode can be seen on copy paper at 2 m/s. One should note that these measurements were obtained under as realistic as possible test conditions, which means very little signal averaging. Also, they are by no means the best that one could obtain because the experimental setup was far from being optimized for paper testing.

CONCLUSIONS

The rationale for the monitoring of elastic stiffness properties during papermaking was presented. However, as essential as these properties are to evaluate the real-time mechanical behavior of paper, additional information must be considered to develop a comprehensive model of the inverse problem of predicting process changes from measurements. The concept of simultaneous detection of FOD and SOD was shown to be of particular interest to determine the degree of built-in stresses in dry paper. An overview of the research program aimed at developing appropriate on-machine instrumentation for elastic stiffness, SOD and FOD determination, and developing a predictive model of process changes revealed the complexity of the endeavor. Demonstration measurements on simulated moving paper at production speeds using noncontact laser ultrasonics technology were shown to be very promising.

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References

1. Fleischman, E.H., "An Investigation of the Elastic and Dielectric Anisotropy of Paper," Ph.D. Thesis, Inst. of Paper Sci. and Tech., Atlanta GA (1981).

2. Berger, B.F. and Baum, G.A., "Z-Direction Properties: The Effects of Yield and Refining," Papermaking Raw Materials, Punton Ed., vol. 1 pp. 339-362 (1985).

3. Baum, G.A., "Elastic Properties, Paper Quality, and Process Control," Appita, 40(4), pp. 288-294 (1987).

4. Charles, L.A., "Effect of Supercalendering on the Strength Properties of Paper", Calendering and Supercalendering Anthology 1985-1993, Tappi Press, Chapter 1, pp. 66-73 (1994).

5. Hwang, C., "Relationships Between Fiber Orientation and Stiffness Properties in Response to Wet Straining and Drying Restraint," M.S. Report, Inst. of Paper Sci. and Tech., Atlanta, GA (1995).

6. Ishisaki, M., "Comparative Study of Fiber and Stiffness Orientation Distributions," M.S. Research Report, Inst. of Paper Sci. and Tech., Atlanta, GA (1997).

7. Mann, R.W., Baum, G.A., and Habeger, C.C., "Determination of All Nine Orthotropic Elastic Constants for Machine-made Paper," Tappi J., 63(2), pp. 163-166 (1980).

8. Freeman, D., "Papermaking Processes and Their Relationships to Mechanical Behavior of Paper," A390 Report, Inst. of Paper Sci. and Tech., Atlanta, GA (1998).

9. Hess, T.R. and Brodeur, P.H., "Effects of Wet Straining and Drying on Fiber Orientation and Stiffness Orientation," J. Pulp and Paper Sci. 22(5), pp. J160-J164 (1996).

10. Haynes, K., "Decoupling of Fiber and Stiffness Orientation Distributions," A390 Report, Inst. of Paper Sci. and Tech., Atlanta, GA (1996).

11. Van Zummeren, M., Young, D., Habeger, C., Baum, G., and Trevelen, R., "Automatic Determinatoin of Ultrasound Velocities in Planar Materials," Ultrasonics, 25(9), pp. 288-294 (1987).

12. Habeger, C.C. and Baum, G.A., "On-line Measurement of Paper Mechanical Properties," Tappi J., 69(6), pp. 106-111 (1986).

13. Brodeur, P.H., Hall, M.S., and Esworthy, C., "Sound Dispersion and Attenuation in the Thickness Direction of Paper Materials," J. Acoust. Soc. Am., 94(4), pp. 2215-2225 (1993).

14. Pankonin, B.M., "Mill Experiences with On-line Ultrasound Based Stiffness Measurements," Proc. 1999 TAPPI Eng./Proc. & Prod. Qual. Conf., TAPPI Press, Altanta, GA (1999).

15. Kopkin, B., "A New Method for On-line Measurement of Strength and Elastic Properties of a Running Paper Web – Background and Mill Experiences," Proc. 85th Annual Meeting, PAPTAC, Montreal, QC, Vol. B, pp. B423-B427 (1999).

16. Brodeur, P.H., Johnson, M.A., Berthelot, Y.H., and Gerhardstein, J.P., "Noncontact Laser Generation and Detection of Lamb Waves in Paper," J. Pulp and Paper Sci., 23(5), pp. J238-J243 (1997).

17. Brodeur, P.H., Gerhardstein, J.P., Habeger, C.C., Jong, J.H., Lafond, E.F., Pufahl, B., Deason, V.A., Schley, R.S., Telschow, K.L., Walter, J.B., Watson, S.M., and Berthelot, Y.H., "Contactless Real-time Monitoring of Paper Mechanical Behavior During Papermaking," Phase I Report to U.S. Department of Energy, Project No. DE-FC07-97ID13578 (1998).

18. Syré, H.R. and Hagen, W., "Improving Paper Quality Through on-line Measurement and Control of Fiber Orientation," Proc. First EcoPaperTech Conf. on Papermaking and Paper Machine Technology, Helsinki, Finland, pp. 51-60 (1995).

19. Drouin, B., Gagnon, R., Schroder, A., Silvy, J., and Butel, M., "L'orientation des fibres et les propriétés mécaniques du papier: méthode de contrôle de l'anisotropie de la feuille," Proc. 47th ATIP Meeting, Grenoble, France, pp. 1-8 (1994).

20. Jong, J.H., Lafond, E.F., Brodeur, P.H., Gerhardstein, J.P., and Pufahl, B.M., "Dispersion of Lamb Waves in Static and Moving Paper to Measure Stifness Using Non-contact Laser Ultrasonics," Proc. 85th Annual Meeting, PAPTAC, Montreal, QC, Vol. A, pp. A145-A148 (1999).

21. Jong, J.H., Brodeur, P.H., and Gerhardstein, J.P., "Measurement and Analysis of Stiffness Properties in Moving Paper Using Non-contact Laser Ultrasonics," Proc. 1999 Int. Paper Physics Conf., TAPPI Press, Atlanta, GA (1999).

22. Brodeur, P.H., Jong, J.H., Lafond, E.F., Gerhardstein, J.P., and Pufahl, B.M., "Laser Ultrasonics for Non-contact Measurement of Paper Stiffness in Non-moving and Moving Paper," Accepted for Publication in J. Pulp and Paper Sci. (1999).

23. Pouet, B., Lafond, E., Pufahl, B., Bacher, D., Brodeur, P., and Klein, M., "On-machine Characterization of Moving Paper Using a Photo-EMF Laser Ultrasonics Method," Proc. SPIE Conf. on Process Control and Sensors for Manufacturing, SPIE, vol. 3589, pp. 160-169 (1999).

24. Gerhardstein, J., Lafond, E., Jong, J., Pufahl, B., and Brodeur, P., "Non-contact Laser Ultrasonics Monitoring of Paper Stiffness Using a Variable Speed/Fluttering Simulator," Proc. 1999 TAPPI Eng./Proc. & Prod. Qual. Conf., TAPPI Press, Altanta, GA (1999).