

Overview of Applications of Ultrasonics in the Pulp and Paper Industry

P.H. Brodeur and J.P. Gerhardstein

Institute of Paper Science and Technology
500 10th St. N.W., Atlanta, GA 30318

Abstract — The pulp and paper industry encompasses a broad range of processes from wood harvesting to debarking, pulping, bleaching, papermaking, and converting operations. In relation to these processes and others, several uses of ultrasonics have been investigated. One generally distinguishes two main categories: a) use of ultrasonic energy in process-related applications, and b) ultrasonic measurement of pulp and paper materials. Examples of applications in the first category include recycled pulp deinking, pulp refining, and water stream clarification. The second category considers applications such as measurement of pulp consistency and evaluation of paper elastic stiffness properties. This paper proposes an overview of applications in both categories and an analysis of the status of ultrasound in the pulp and paper industry. Also, the use of acoustic radiation pressure to manipulate liquid-suspended particles and laser

ultrasonics techniques to probe paper stiffness properties on moving paper are discussed.

INTRODUCTION

Wood harvesting, debarking, pulping, bleaching, papermaking, and converting operations are among the numerous processes involved in the manufacturing of paper materials. Altogether these processes involve a large matrix of scientific and engineering disciplines from forest biology, organic chemistry and physics, to chemical and mechanical engineering. Because the pulp and paper industry has extensive needs for processes and measurements, it has fostered over the years the investigation of a relatively large array of ultrasound applications. This is indeed verified by a diversified list

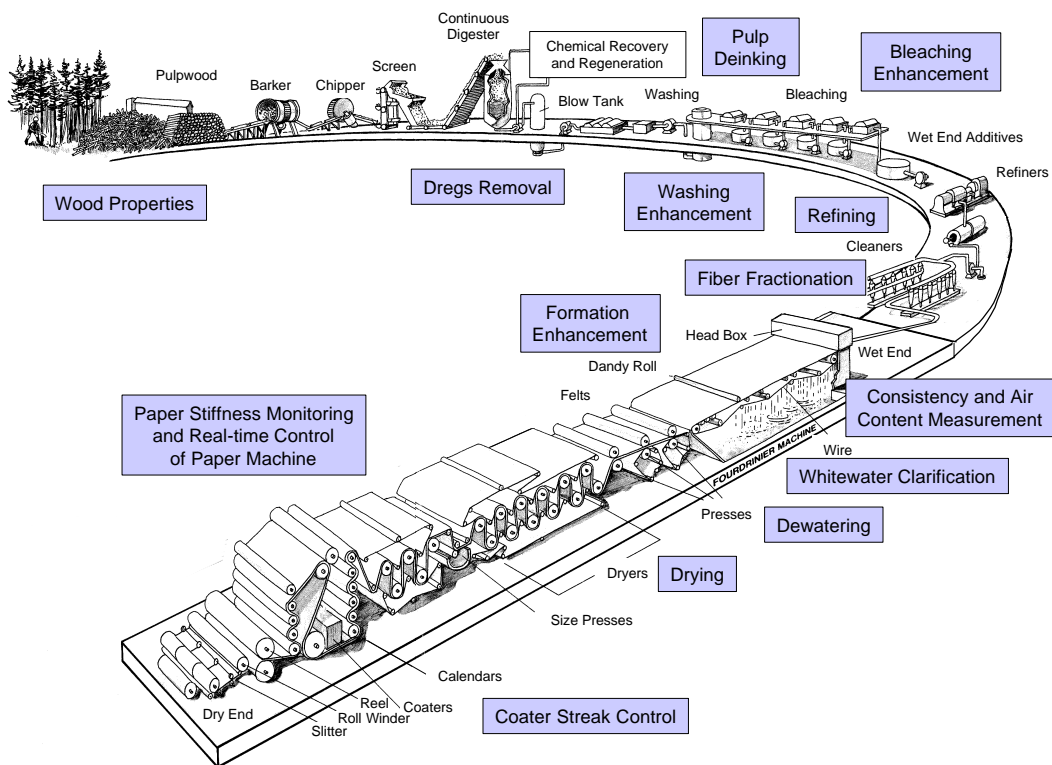


Figure 1. Schematic of the papermaking process and potential uses of ultrasonics.

of applications reported in the literature. Laine et al. reviewed in 1977 several applications of ultrasound in pulp and paper technology [1]. Since then, many more applications have emerged. Figure 1 illustrates a simplified schematic of pulp and paper operations from wood harvesting to paper roll production on the dry end of a paper machine. Also shown in this figure are potential applications of ultrasonics which have been the subject of previous studies (see below). Applications of ultrasonics during converting operations (e.g., printing and manufacturing of corrugated boxes) and for paper testing are not shown. Also, uses of ultrasound for thickness, roll diameter and flow velocity measurements are not considered here.

Applications of ultrasonics in the pulp and paper industry can be categorized into process and measurement applications. The first category considers processes such as enhancement of pulping and bleaching processes [1], depolymerisation of cellulose [1], refining of pulp suspensions [2-6], pulp deinking and treatment of wastepaper [4, 7-9], agglomeration and reorientation of liquid-suspended fibers [10, 11], fractionation of pulp suspensions [12, 13], paper formation enhancement in the headbox of a paper machine [14] and glue application for single-faced corrugated board [15, 16]. The second category refers to the measurement of pulp consistency [17], air content in fiber suspensions [18], compactibility of a wet fiber mat [19], liquid penetration in paper [20, 21], evaluation of tissue softness [22], detection of delamination in paper products [23], acoustic emission monitoring of paper [24, 25], and laboratory and on-machine characterization of paper elastic stiffness and end-use properties using dry-contact [26-35], air-coupled [36, 37], and laser-based methods [39-41].

In this paper, the intent is not to systematically review applications of ultrasound but provide a perspective of the status of ultrasonics in the paper industry and report on some recent developments as a means to stir up a wider interest toward research and development in this area.

STATUS OF ULTRASONICS

As informative as Figure 1 can be, it cannot mask the fact that research and development efforts over the years did not translate into a wide spread usage of ultrasonics in the industry. It is probably correct to state that the penetration rate of ultrasonics has yet to exceed the curiosity level and remains low in comparison with its potential.

There are explanations to the limited usage of ultrasonics. First, it is generally agreed that the pulp and paper industry is a mature industry in the sense that its' low-value commodity products have been around for a long time. This implies that technological advances in the production line are incremental over time rather than revolutionary, thus limiting the introduction of novel

process or test methods. Moreover, the massive capital investment typically required to build a new paper mill or modernize existing equipment (higher than in any other industry) leads by itself toward the use of available but improved techniques. The potential for disastrous financial consequences attributed to technical difficulties in implementing full-scale commercial systems of unproven techniques outside the laboratory or the pilot-scale level is another factor limiting the use of relatively unconventional techniques. Also, the belief that new methods may fail the test of harsh environment conditions or may not work first time support the maintaining of existing and predictable process and test practices, even though productivity or product quality might otherwise be significantly improved.

In a power hungry industry where low-profit margins are the norm, reduction of power consumption is an industry-wide major objective. This implies that energy-related applications of ultrasound are not especially welcome due to their perceived inefficient use of energy. This perception counters anticipated quality benefits and works against the development and demonstration of ultrasonic processes that are energy-efficient and/or can provide unique solutions to unsolved problems.

Difficulties in implementing ultrasonic processes are best stigmatized by the process of wood pulp refining. Refining is a fundamental step of the papermaking process. Its purpose is to fibrillate fibers and increase their degree of flexibility and swellability prior to paper formation on a paper machine (see Figure 1). Without this mechanical treatment, fibers will not bond very well to each other and the network of fibers (paper) will be of poor quality. Modifications to the fibers are achieved through the use of counter-rotating disks with patterns of grooves and edges on their surface. As one might expect, this is a very energy intensive process. Moreover, while desirable fiber properties are obtained, other less desirable effects such as fiber cutting and kinking are also produced. Lack of controllability seriously limits property selectivity. Considering that disk refining is somewhat of a compromise technology, several other refining methods have been devised. One of them, ultrasonic refining, has been the subject of several studies [2-6]. The goal is to use cavitation and microstreaming to refine fibers. The method is attractive because frequency and power level can be used to control modifications to the fibers. Also, on-line treatment in a pipe flow can be envisioned. However, exoticism, inefficient use of energy, and conflicting observations have plunged this application into controversy. In retrospect, this is largely attributed to the absence of a systematic scientific investigation. Does ultrasonic refining live up to the claim of superior controllability? Does cavitation fibrillate fibers or simply shatter fiber surfaces and create unwanted fiber debris? Can it ever be an energy-efficient process? Definitive answers to these questions are unavailable.

Now, focusing on the status of ultrasonic measurements, papermakers have long relied on the laboratory testing of various paper strength properties to assess the quality of their products. Some of the test methods were conceived more than fifty years ago with questionable scientific merit and are still in use today. When the long-term monitoring of trends is the main objective, mechanical strength measurements are adequate even though they are destructive, operator-sensitive, and time consuming. However, in the context of product optimization they are inadequate. Since it is known that paper stiffness properties, as obtained using nondestructive ultrasonic techniques, correlate to strength properties in an empirical manner, it has long been demonstrated in the laboratory that ultrasonic test methods can provide significant benefits to the industry [31]. But because stiffness measurements do not generate equivalent numbers to strength parameters, they received very limited attention in the production environment.

In a rare instance where ultrasonics has translated into a successful niche market, laboratory commercial instruments are used to excite and receive Lamb waves (S_0 mode) at various angles with respect to the principal axis of the paper machine (machine direction or MD), and hence evaluate the planar stiffness orientation distribution [42, 43]. These instruments are designed to process cross-machine paper strips cut from every successive jumbo roll during production. The reason for the success is not related to the usefulness of velocity or stiffness measurements per se, but to the angular determination of maximum stiffness with respect to MD. Since the stiffness orientation distribution (SOD) is sensitive to the geometrical fiber orientation distribution (FOD) in the plane of paper (fibers are preferentially oriented along MD during formation on the wet end of the paper machine), the angular offset of maximum stiffness provides an indirect assessment of fiber misalignment with respect to MD. Fiber misalignment is symptomatic of equipment malfunctioning during formation and can lead to undesirable effects during converting operations. The Z-fold stack lean effect of continuous sheets and business forms is a direct consequence of fiber misalignment [44]. Also, twist warp in corrugated board panels can impair the manufacturing of boxes [45].

Although laboratory stiffness measurements provide valuable and very often otherwise information unavailable to optimize material properties, their real value during production is their unique potential for real-time stiffness monitoring of a moving paper web during production, and hence, real-time control of the papermaking process (see below) [28, 31]. It is believed that nondestructive ultrasonic testing of paper, either in the laboratory or during production, will inevitably receive full consideration as market economics will shift production goals from tons per day (quantity goals) to product uniformity and optimization (quality goals).

Next, two recent technological developments accomplished at the Institute of Paper Science and Technology are briefly discussed.

PROCESS APPLICATION: ON-LINE SEPARATION

IPST has been involved for some time in the study of pulp suspension flows interacting with an ultrasonic wave field [12]. This work led to the development of a multi-purpose in-line ultrasonic separation technology for use in the pulp and paper industry [13]. Contrary to previous research work about ultrasonic separation methods (see Ref. 13), the goal is to devise a system capable of processing a large quantity of material at production flow rates (e.g., 1000 to 5000 L/min). This implies several compromises such as simplified separation principles and large specific throughput at the expense of excellent separation efficiency. Also, energy efficiency and robustness of equipment are other major issues to be addressed.

A schematic of a laboratory in-line separation setup is shown in Figure 2. An array of transducers is mounted on one of the walls of a rectangular cross-section pipe in such a way as to produce a traveling ultrasonic wave field propagating normal to the flow direction. Acoustic radiation pressure is used to redistribute liquid-suspended particles as they penetrate the transducer-absorber section from bottom to top. The redistribution mechanism is predominantly based on particle radius. The end result is at least two output streams with different consistency levels. Possible applications are the redistribution of fibers into slender-enriched and coarse-enriched fractions, clarification of water streams, and thickening of pulp suspensions.

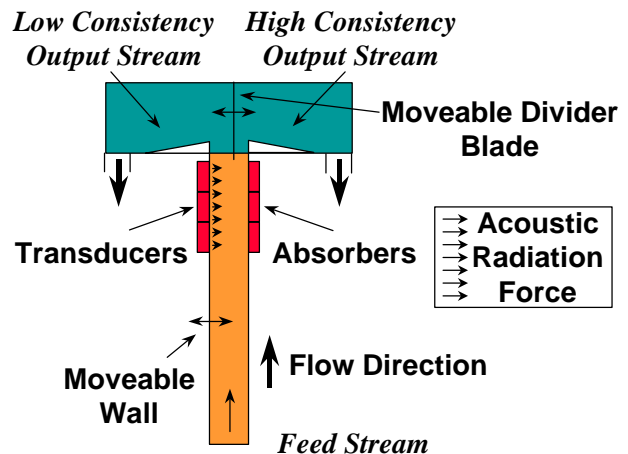


Figure 2. Schematic of in-line ultrasonic separation apparatus.

Figure 3 shows a close-up of the transducer-absorber section and deflection of unbleached softwood fibers as

they interact with the ultrasonic field. Figure 4 illustrates the concept of in-line ultrasonic clarification of a whitewater stream. Whitewater is the filtrate from the forming fabrics on the wet end of a paper machine (see Figure 1). In this example, the consistency (percentage by weight of oven-dry solids) is 0.08%, the flow velocity is 0.5 m/s, the ultrasonic frequency is 150 kHz, and the electrical intensity applied to the transducers is 12 W/cm². One can see that the solids moved from the transducer side (left) to the absorber side (right). A mechanical divider located on top of the ultrasonic section is used to separate the clarified and concentrated streams.

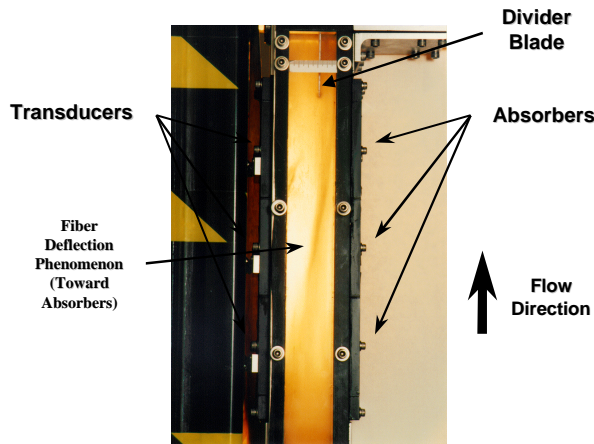


Figure 3. Deflection of flowing unbleached softwood fibers in the transducer-absorber section of Figure 2. Fibers are deflected toward the absorbers.

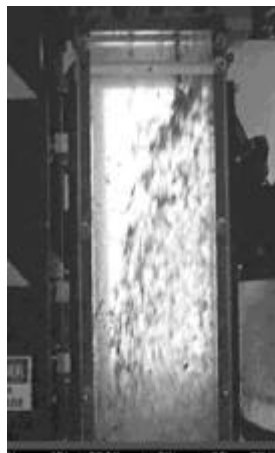


Figure 4. Photograph of a whitewater stream subjected to acoustic radiation pressure. Transducers and absorbers are located on the left and right sides, respectively. A mechanical divider blade is used to separate the clean and concentrated output streams.

MEASUREMENT APPLICATION: ON-MACHINE STIFFNESS MONITORING

Elastic stiffness properties are known to be sensitive to fundamental papermaking processes such as refining, fiber orientation during formation (MD/CD anisotropy ratio), wet pressing, wet straining, and restrained drying [31, 33-35]. This is illustrated in Table 1. Figure 5 displays a set of in-plane stiffness polar diagrams as obtained using an experimental ultrasonic dry-contact method [30]. This method involves the propagation of Lamb waves (S_0 mode) at different angles with respect to machine direction. Measurements were performed on laboratory oriented handsheets prepared under different wet straining and restrained drying conditions. One can see that machine direction stiffness (C_{11}) increases when wet straining is applied. Also, cross-machine direction stiffness (C_{22}) decreases when paper is allowed to shrink in the CD direction during drying.

Table 1. Papermaking Processes vs. Paper Elastic Stiffness Properties.

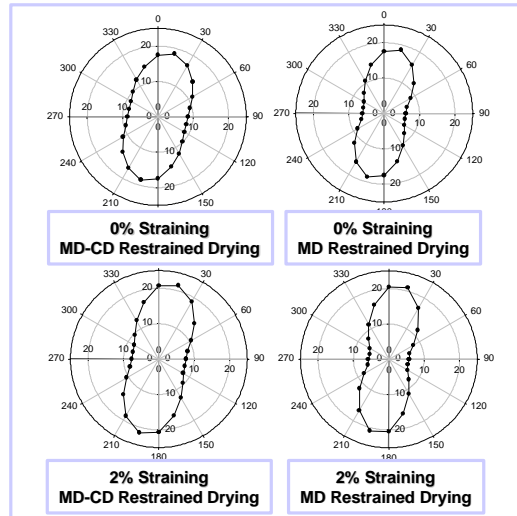
Elastic Stiffness Constants	Refining Level	MD/CD Anisotropy Ratio	Wet Pressing Level	MD Wet Straining Level	Restrained Drying
	From Low to High	From Low to High	From Low to High	From Low to High	From Full Restraint to CD only
MD: C_{11}	↑	↑	↑	↑	0
CD: C_{22}	↑	↓	↑	↓	↓
ZD: C_{33}	↑	0	↑	↓	0
MD-CD: C_{66}		↓	↑	0	
MD-ZD: C_{55}		↑	↑	↓	
CD-ZD: C_{44}		↓	↑	↓	

Table 1 and Figure 5 show that there is a significant interest in monitoring these properties on a moving paper web as a means to provide the necessary information to control a paper machine. Until recently, much of the research and development work about on-machine ultrasonic stiffness focused on the use of contact transducers (see Ref. 41 for a summary account of on-machine ultrasonic stiffness methods). Considering limitations with the use of contact transducers such as potential damage to the web and difficulty of implementation for lightweight paper grades such as copy paper, newsprint or tissue paper, the demonstration of non contact techniques must be addressed. In that regard, laser-based methods to excite and detect Lamb waves in non moving paper were recently explored [39-41]. Successful measurements were obtained on different lightweight and heavyweight grades in both machine and cross-machine directions using a Mach-Zehnder interferometer setup [41].

Since the ultimate goal is to perform non contact measurements on a moving web at production speeds, a

Control Sample
(MD/CD Stiffness Ratio: 2.1)

MD Elongation



CD Shrinkage

Shrinkage Elongation Rotation

Figure 5. In-plane stiffness polar diagrams for laboratory oriented handsheets prepared under different process conditions. Handsheets were cut with a simulated fiber misalignment angle of 15 degrees with respect to machine direction prior to straining and drying. The control sample MD/CD stiffness ratio is 2.1.

major research effort was recently undertaken at IPST to perform demonstration experiments using a specially-built moving web simulator in a laboratory setting. Figure 6 shows a partial photograph of the experimental setup. One can see the web simulator and some of the excitation/detection optics.

Different interferometric methods likely to be successful with moving paper (which has a very rough and poorly reflective surface) were investigated. Figure 7 shows a series of measurements at different web speeds

for copy paper. Lamb waves were excited using a pulsed Nd:YAG laser in a thermoelastic regime and detected using a laser interferometer. The fundamental symmetric and asymmetric modes for Lamb waves (S_0 and A_0 modes) were observed up to 6 m/s. The A_0 mode is observed for copy paper up to 25 m/s, i.e., at production speeds. These results, although preliminary, are very promising and indicate that the concept of laser ultrasonics applied to a moving paper web is likely to be successful on a paper machine.

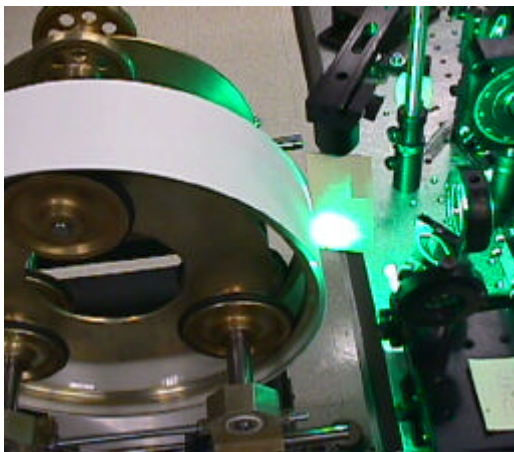


Figure 6. Partial view of the laser ultrasonics setup for excitation and detection of Lamb waves in a simulated moving paper web. The setup is located in a temperature/relative humidity controlled laboratory.

CONCLUSIONS

We have seen that there are several opportunities for process and measurement applications of ultrasonics in the pulp and paper industry. However, very few of these applications have moved beyond the laboratory or pilot-scale level. Also, recent technology developments involving in-line ultrasonic redistribution of liquid-suspended particles and laser ultrasonics measurement of Lamb waves in a moving paper web were discussed. Finally, the technique likely to have the most significant impact in the industry in the foreseeable future is the monitoring of paper elastic stiffness properties during papermaking.

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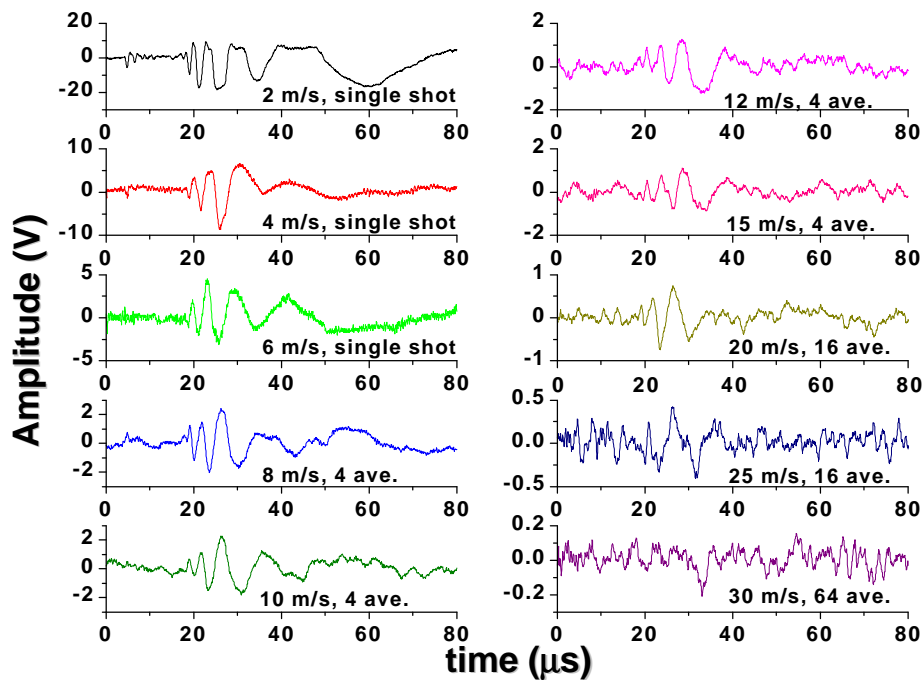


Figure 7. Typical copy paper results obtained at different web speeds using a laser-based ultrasound system. Measurements were performed in the cross-machine direction in a thermoelastic regime. Also, the separation distance between the source and detection points was set constant to 10 mm.

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