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Stiffness properties and stiffness orientation distributions for various paper grades by non-contact laser ultrasonics

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Abstract

The stiffness properties, especially flexural rigidity (FR), out of plane shear rigidity (SR), and stiffness orientation distributions (SOD) are characterized for various paper grades, by a laser ultrasonics instrument. Laser ultrasonics generation is achieved through thermal dilatation by point focusing of a pulsed laser beam onto the surface of the specimen. By probing the excited broadband ultrasound propagating in the samples, the velocities dispersions are obtained and the materials properties are extracted. The measured FR and SR along machine direction (MD) and cross direction (CD) are presented for 10 paper samples ranging from thin copy papers to heavy linerboards. The SOD polar diagrams for some of the samples are also presented and discussed. The relationships of FR, SR, Young's and shear moduli with basis weight are discussed. It is observed that both the Young's and shear moduli tend to decrease significantly when the basis weight increases, going from copy paper to linerboard grades. We also found that SR reaches a maximum value and then decreases when the basis weight increases to 150 g/m^2 and above. This unusual behavior of SR can be explained by the noticeable reduction of shear modulus for heavy linerboards.

Keywords: Laser ultrasonics; Stiffness properties; Non-contact; Non-destructive testing

1. Introduction

Baum stated in a landmark paper published in 1987 the following [1]: "the elastic properties of paper form a basic set of parameters which are useful for monitoring the effects caused by changes in process variables, capable of predicting end use performance, and overall, help to provide a better understanding of the fibrous network we call paper. Elastic parameters also are important in product design and modeling, e.g., in the construction of tubes, boxes, food containers, etc. Eventually their use will help to control the paper machine automatically. Because most of the elastic parameters needed to describe paper can now be determined easily and non-destructively using wave propagation methods, the opportunity exists to move forward in each of these areas".

To tackle the inverse problem presented by Baum is not straightforward. It is believed that an experimental approach must be first investigated to gather hard evidence. Also it is postulated that existing information obtained on a paper machine (grammage, thickness, moisture content, web temperature) and information such as stiffness properties, the stiffness orientation distribution (SOD) can be used in a meaningful manner to provide a preliminary layout of a model to control the papermaking process [1–9].

It is widely recognized that pulp injection direction, methods and wire mesh structure all contribute to the final paper stiffness, SOD, etc. properties. The subsequent water drains process such as pressing and drying can also contribute to it. The paper mechanical properties also depend upon the built-in stresses, which can contribute to the process such as wet straining and/or restrained drying [1–2]. To achieve real-time control of the papermaking process, it is necessary to develop appropriate instrumentation to determine stiffness properties, SOD

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and demonstrate the functionality of the instruments in the laboratory, then in a mill environment.

A laser ultrasonic instrument has been developed for the purpose of laboratory demonstration. Unlike conventional contact ultrasonics methods, this instrument uses a pulsed laser to generate ultrasound in specimens [10–13], and uses a second CW laser to probe the excited ultrasound. This enables a fully non-contact characterization of the properties of a large variety of paper specimens, ranging from light copy papers to heavy paperboards. The non-contact characteristic of the instrument is a valuable advantage over other mechanical or contact testing techniques since there is no probe-induced perturbation of the medium observed [10–13]. It also provides the possibility to tackle Baum's real time process control.

To demonstrate the functionality of the laser ultrasonic instrument, different grades of paper and paperboard samples were obtained from different manufacturers or commercial suppliers and their stiffness properties and SOD were characterized. Samples were chosen based on percentage of total paper production and those that would benefit most from real-time stiffness measurements. Moreover, they represented a wide range of grammages.

Some of the main stiffness properties, namely flexural rigidity (FR) and shear rigidity (SR) along the machine direction (MD) and cross direction (CD) are reported. Of all the mechanical parameters that could conceivably be measured "on-line" (on the papermaking machine), FR is the one most directly related to important end use performance and the one of most practical value [1–9]. Out of plane shear rigidity is a sensitive indicator of fiber bonding and is an important contributor to in-plane compressive strength. In addition to monitoring end-use properties, real time measurements of FR and SR are potentially useful as inputs for feedback process control.

The FR and SR along MD and CD for 10 samples (ranging from copy paper to heavy linerboard) are tested by the laser ultrasonics instrument and are reported in the later sections of this paper. The FR and SR SODs for some of the samples are presented using a polar diagram. The arrangement of this paper is as follows: the theory of ultrasonic plate waves is first reviewed, then, the instrument is briefly described. And then we present and discuss the measurement results as well as interesting aspects such as misalignment of maximum value of SOD with MD in copy paper samples and large MD/CD ratios in a 42 lb brown linerboard.

2. Experimental procedure

2.1. Ultrasonic A_0 wave and laser ultrasonics (LU)

Ultrasound can be used to probe fiber orientation, tensile breaking strength, compressive (buckling) strength, bending stiffness, shear rigidity, and other mechanical properties in paper [10–18]. These mechanical properties empirically correlate with elasticity of the paper, which in turn correlates with the propagation velocity of ultrasonic Lamb (plate) waves through and along the paper sheet [18–20].

Paper is a thin plate and Lamb waves propagate well in it. Because of the fibrous structure of paper and of the scattering nature of paper (10 μm diameter fibers and 10 μm holes typically), only low-frequency ultrasonic waves (<1 MHz) can propagate without being attenuated after a few mm travel. Hence even if the acoustic source can generate signals at high frequencies, only low-frequency waves can be detected, and consequently only the first-order antisymmetric Lamb wave (see Fig. 1) named A_0 and the first-order symmetric Lamb wave named S_0 in a paper sheet [11–13,21] can be observed with a decent signal-to-noise ratio (Fig. 2).

The A_0 and S_0 waves in paper are different from many points of view. First the A_0 wave at low frequencies is mainly an out-of-plane wave, i.e. generates displacements in a direction perpendicular to the surface of the web. The phase velocity of the A_0 mode depends on the frequency, FR, SR and basis weight. The S_0 wave is almost exclusively an in-plane wave, i.e. generates displacements in a direction parallel to the surface of the web. Second, the LU-generated amplitude of the S_0 wave is much smaller than the amplitude of the A_0 wave, consequently in most cases only the dominant A_0 waves can be detected.

The LU metrology uses pulsed laser irradiation to induce ultrasonic A_0 wave in a test object via three mechanisms: thermal-elastic (thermal dilatation), ablation and plasma [10]. The latter two occur when the density of laser energy per unit area goes above a given threshold. The resulting ultrasonic wave packets are measured often in a non-contact, non-destructive manner using one form of interferometer. LU often monitors an ultrasonic waveform

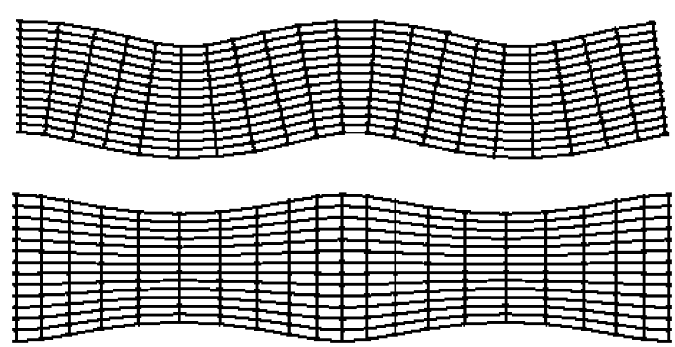

Fig. 1. A_0 antisymmetric (top) and S_0 symmetric (bottom) mode shapes as viewed from the edge of a sheet of paper.

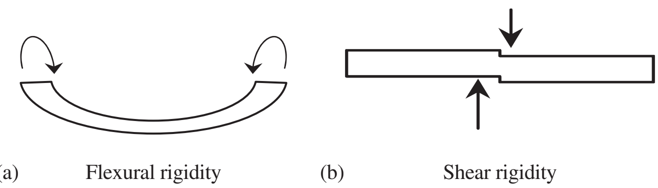

Fig. 2. Schematic to explain flexural rigidity and out of plane shear rigidity of a thin plate.