Title

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LASER ULTRASONIC MEASUREMENT OF ELASTIC PROPERTIES OF MOVING PAPER: MILL DEMONSTRATION

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ABSTRACT. An automated sensor has been developed for use during paper manufacture that can measure flexural rigidity (bending stiffness). Based on laser ultrasonic technology, this sensor provides continuous noncontact on-machine measurements on paper having area densities from 35 to 205 g/m^2, moving at commercial manufacturing speeds, at any angle in the plane of the sheet. It was demonstrated on a high speed printing paper grade machine during commercial production. For that demonstration, the sensor was integrated into an existing scanning sensor system. Cross-direction profiles of flexural rigidity had the expected shape, and compared well with traditional bending stiffness measurements on samples collected for that comparison.

Keywords: laser ultrasonic analysis, bending stiffness, industrial applications
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INTRODUCTION

Laser ultrasonics [1] has been applied in recent years to measurement of mechanical properties of paper in the laboratory [2,3]. Further laboratory demonstrations of LUS on moving paper demonstrated the possibility for routine measurement of these properties during manufacture, opening the way to feedback control of the papermaking process based on these measurements [4,5,6]. We have developed a flexural rigidity (bending stiffness) sensor prototype for installation on commercial papermaking machines.

In this paper we present a brief summary of the basic design (hardware, data acquisition, signal analysis), which has been described in detail previously [7], and report in detail on further hardware and software developments, and the results from a demonstration of the sensor on a papermaking machine during commercial operation.

Sensor Hardware

The ultrasound generation system consists of a pulsed Nd:YAG laser (New Wave Tempest 10) that delivers a 15 nanosecond pulse at 1.06 µm into an optical fiber, which transmits the laser pulse over a distance of approximately 8 m to the sensor where it is focused onto the paper sheet with a 10mm focal length aspheric lens. The laser pulse energies ranged from 3 to 8 mJ. The detection interferometer beam was focused onto the paper at a position separated by from 5 to 10 mm from the position where the generation beam was focused. The generation spot was positioned by X-Y positioning servos from 4 to 10mm away from the detection spot in the Machine Direction (MD, the direction in which the sheet is moving) or Cross Direction (CD, the direction in the plane of the sheet perpendicular to MD).

The ultrasound detector is a Mach-Zehnder He-Ne laser interferometer (Polytec-PI CLV1000/OVD02), coupled with a scanning mirror to move the detection laser beam to track paper motion, and a timing system to fire the generation laser when the detection beam is in the proper position on the paper surface.

Data Collection

Ultrasound-induced interferometer signals are recorded with a desktop computer equipped with an oscilloscope card (Gage Compuscope 1250). LabVIEW-based software collects data from the ABB scanning system such as basis weight (area density), water content, and sheet speed. These data are used to correct stiffness measurements for the effects of variations in these properties.

Signal Analysis

The Fourier transforms of two ultrasonic signals, recorded at different excitation-to-reception separations (d) (usually 5 and 10 mm), are used to calculate the phase velocity C as a function of angular frequency, ω. A model equation is fitted to the experimentally determined plot of C versus ω. This fit, along with the area density of the sheet, which is simultaneously measured by another sensor, determines the value of the flexural rigidity. Flexural rigidity (FR) differs slightly (for paper it is typically about 9% larger) from Bending Stiffness (BS) through a term that depends on the in-plane Poisson's ratios (ν_{xy} and ν_{yx}), and is for practical purposes a constant:

$$FR = BS/(1-\nu_{xy}\nu_{yx}). \tag{1}$$

SENSOR CONFIGURATION FOR THE MILL DEMONSTRATION

Sensor Installation on the Scanner Platform

This prototype sensor is designed to be mounted "piggy back" on the upstream end of the "head package" of a commercially available scanning system (Smart Platform by ABB, Inc.), designed for papermaking machines. The head package contains various sensors and scans the width of the sheet, perpendicular to the direction of sheet motion. A drawing of the scanner platform with our sensor installed is shown in Figure 1.

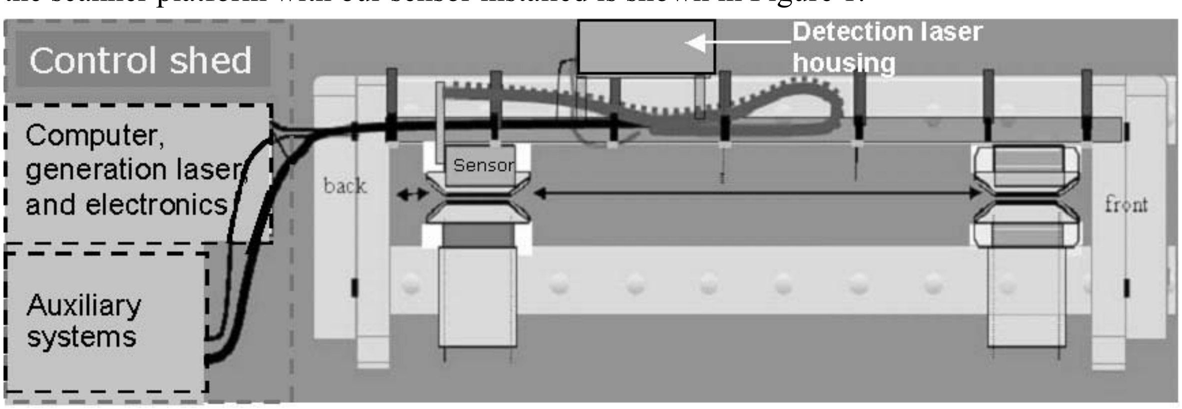

FIGURE 1. Drawing of ABB Corp.'s "Smart Platform" sensor scanning system, with the sensor installed

FIGURE 2. The sensor installed on the sensor scanner "platform" on the papermaking machine during the mill demonstration.

The control shed, a temporary structure located about 5m away from the scanner platform housed the generation laser, desktop computer, the interferometer demodulation electronics, a desk and a few chairs. An "auxiliary system panel" also located about 3m from the scanner platform contained apparatus for purifying and controlling the pressure and flow rate of several compressed air streams to the sensor, and the 3-axis motor controller for the sensor's two translation stages and detection system scanning mirror.

Cables carrying electrical power, signals, compressed air, optical fibers delivering generation laser pulses, the detection laser beam, etc. between the sensor and control shed and auxiliary system panel were suspended along the scanner platform by a cable chain (Igus, Inc.) which rolled into and out of a supporting track as the head package scanned back and forth across the sheet.

The He-Ne laser for the interferometer was located on the top beam of the sensor scanner, as the optical fiber carrying the beam to the sensor was limited (by Polytec) to a maximum length of 10m, which was too short to allow it to be placed anywhere else. Figure 2 is a photograph of the sensor installed on the head package.

Data Acquisition and Signal Processing Developments

New algorithms for data acquisition and signal processing were developed in preparation for the mill demonstration. Ultrasound signals were not used if detection beam light collection by the interferometer fell below a threshold value. All accepted signals collected for an entire scan of the sensor in one direction across the sheet were stored for the duration of the current and following scans. The signals were divided into 10 "data bins", each bin associated with a range in the cross direction of the sheet over which the scanner travels. Signals within each bin are averaged. The bin ranges overlap considerably to increase the number of signals averaged to about 15-25, depending on how many signals were rejected. As the scanner travels in one direction, only the short (or long) separation distance signals are collected. During the following scan in the reverse direction, the long (or short) separation distance signals are collected. A pair of averaged (long and short separation distance) signals are processed to extract the flexural rigidity which is assigned to the center of each data bin's CD range. Thus, during every scan flexural rigidity is

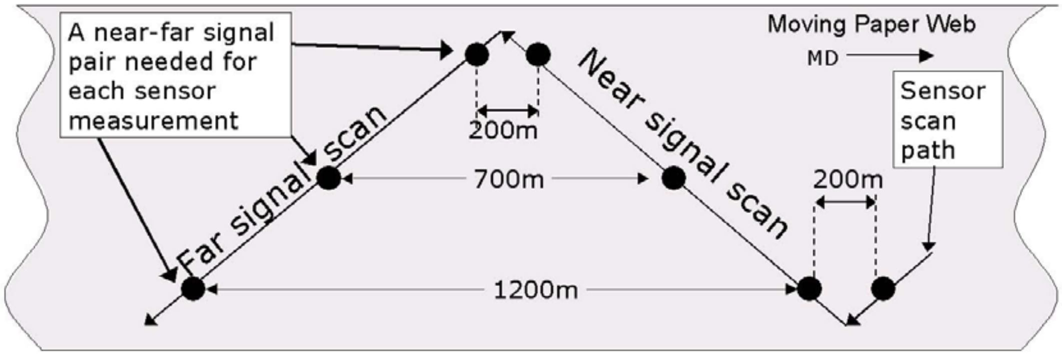

FIGURE 3. Diagram illustrating how the MD resolution of the sensor measurement during scanning varies with CD position and also alternates from one scan to the next.

calculated using signals collected during the current and previous scan. Each averaged signal is used twice to calculate two sequential flexural rigidity values for its CD position.

Since the measurement during scanning requires signals from two sequential scans, the MD spatial resolution of the measurement varies with CD position, as determined by the scan rate and the web speed. This resolution also alternates between higher and lower values, whose difference is greatest at the ends of the scan range, and is zero only at the center of the scan range. This is illustrated in Figure 3. At the ends of the scan range the MD resolution alternates between 200 and 1200m. This difference gradually decreases to zero at the center of the scan range (and web) where the resolution is a constant 700m.

Flexural rigidity measurements were transmitted to the mill's central data collection system in real time. All raw ultrasonic signals, ABB sensor data, scanner position, time, and numerous other variables and conditions were stored on the desktop computer in log files which could be reprocessed to re-determine flexural rigidity values after the mill demonstration. All mill demonstration flexural rigidity data presented in this paper were recalculated using these log files.

RESULTS

The main mill trial objective was to demonstrate that the sensor measured flexural rigidity of the sheet as a function of CD position. A secondary objective was to verify a reasonable relationship between the sensor measurements and the traditional "Gurley Stiffness" test that the mill relies on as a measure of bending stiffness. Other goals included initial explorations of the sensitivity of the sensor's measurement to process changes that affect bending stiffness such as "calendering" (which affects sheet thickness), filler loading (in this case starch), and MD tension, which does not affect the bending stiffness but affects the measurement by changing ultrasound velocity.

Comparison of CD Profiles of Sensor FR with Gurley Stiffness

At the mill that hosted our demonstration, the Gurley Stiffness test is routinely used to evaluate bending stiffness, so we chose that test as a standard for comparison with our sensor's measurement.

The Gurley test is a traditional paper stiffness test in which a sheet sample of specified proportions is clamped at one end and the force required to bend the free end a specified distance is measured[8].

There were two challenges in comparing the Gurley test with our laser ultrasonic measurement. The Gurley test takes about one second to complete, whereas our sensor's measurement flexes the sheet on the 10^{-5} to 10^{-4} second timescale. The viscoelastic nature of paper and the large difference in the timescales of the Gurley and the laser ultrasonic measurements give rise to a complication in comparing the measurements. Since paper is viscoelastic, the force required to keep a paper sample "bent" decreases by about 8% per decade increase in time. Thus we can expect that the stiffness of a paper sample measured on the Gurley timescale to be about 60-70% of what it would be on the laser ultrasonic timescale.

A second complication is that the Gurley test produces a measurement that is not well defined in terms of elastic or material properties, though it is closely related to the bending stiffness, which is defined as

$$BS = EI = Et^3/12 \tag{2}$$

where E is Young's modulus, I is the bending moment of inertia and t is sheet thickness. The curvature imposed on the paper sample by the Gurley test is not constant throughout the bent length. Therefore a pure bending stiffness is not measured, and the relationship of the Gurley stiffness to bending stiffness (and our sensor's measurement) is not well defined. However, an empirical relationship (i.e., a conversion factor) between Gurley stiffness and bending stiffness, or our sensor's measurement of flexural rigidity, can be determined by making Gurley measurements and laser ultrasonic measurements on the same samples. We found that the most convenient materials to use were metal foils because they are elastic, so that stiffness does not vary with the timescale of the measurement, and because the flexural rigidity can be calculated from well-known elastic and physical properties (Young's modulus, Poisson's ratio, and density) of these materials. Together, these factors allow evaluation of the accuracy of the laser ultrasonic measurement, at least for the metal foils studied, and more importantly, give a basis for estimating flexural rigidity from Gurley data. The comparison of laser ultrasonic measurement of flexural rigidity of metal foils to the calculated values is shown in Figure 4a, and the relationship between Gurley stiffness and the flexural rigidity of the metal foils is shown in Figure 4b.

Applying this conversion to Gurley measurements on paper gives the flexural rigidity of the sheet on the Gurley timescale, so we still expect the converted Gurley measurements to have smaller values than the laser ultrasonic measurements.

Both MD and CD bending stiffness of the "web" (the paper sheet at all stages of the manufacturing process) vary significantly across its width, from highest stiffness at or near the center to lowest at the edges of the sheet. This "frown" shaped CD profile is well known to papermakers, who generally want to minimize or flatten it. Therefore we chose to present our flexural rigidity data as CD profiles.

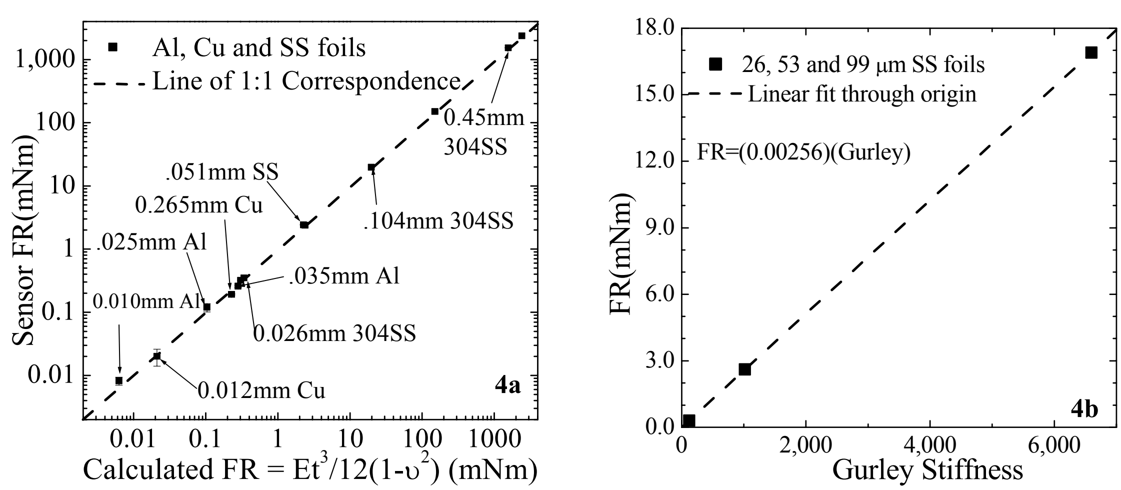

FIGURE 4. Laser ultrasonic measurement of flexural rigidity of metal foils compared to **a.** the calculated FR values; **b.** Gurley stiffness measurements

Ideally, a comparison of a CD profile of web bending stiffness derived from Gurley measurements to the profile measured with our sensor should be a comparison of measurements made on the same paper sample. The only region of the sheet available for Gurley testing was that on the surface of the 40-ton rolls of paper that were being produced. Therefore, a “CD strip” about 12 inches wide in the MD and 33 feet long in the CD (the full web width) was cut from the end of the roll. The sensor measurements being made at the same time as (what was to become) the CD strip was passing under the sensor were selected for comparison with Gurley measurements made later on the CD strip. The CD strips were collected from four rolls during the mill trial. For three of the strips, the CD stiffness was measured. For the fourth CD strip, the MD stiffness was measured. The resulting CD profiles of Gurley stiffness data were converted to flexural rigidity using the conversion factor obtained with metal foils. These “Gurley FR” profiles were then compared to the laser ultrasonic FR profiles, as shown in Figures 5a and 5b.

Figure 5a shows sensor and Gurley FR CD profiles of CD stiffness for the CD strip cut from roll 280. As expected, the CD profile is frown-shaped, and the Gurley measurements (as FR) are about 30% lower due to the viscoelastic effect described above.

Figure 5b shows MD stiffness data (also as CD profiles) for roll 252. Note that the stiffness is three to four times greater in the MD than in the CD (Fig. 5a), and that the profile is much flatter. These differences between MD and CD stiffness coincide with the experience and expectations of mill personnel. The larger MD stiffness is due to the predominant MD alignment of fibers in the sheet.

For the sensor data in Figures 5a and 5b, since the sensor was scanning (moving) in the CD as the 15 –25 signals needed for averaging were collected, overlapping CD ranges denoted by horizontal error bars are associated with the data points, which are located at the centers of their ranges. Notice that these ranges overlap considerably. The CD position “error” bars on the Gurley data are 32 inches long (and don’t overlap) because the 350-inch CD strip was cut into (eleven) 32-inch pieces for Gurley testing. In Fig. 5a, the FR error in the Gurley data is the average standard deviation of repeat measurements for five of the eleven positions on the CD strip. No other Gurley measurements were repeated. In Fig. 5b, the FR errors in the Gurley data are estimated to be the same fraction of the CD-averaged Gurley stiffness as in Fig. 5a.

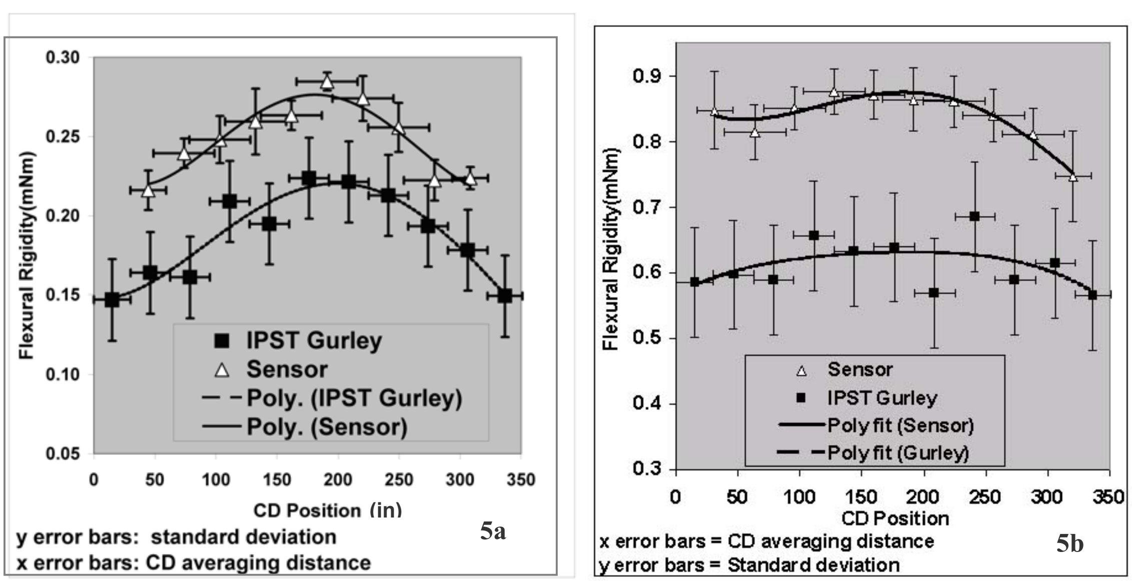

FIGURE 5. Comparison of CD Profile of flexural rigidity measured by sensor on moving paper vs IPST Gurley measurements on the CD strip converted to FR with the factor from metal foil data **a.** CD FR of Roll 280; **b.** MD FR of Roll 252.

Comparison of the standard deviations in the sensor data with that in the Gurley data in both plots indicate that there is less measurement uncertainty in the sensor data. Gurley measurements are notoriously sensitive to variations in sample preparation (particularly curvature) and technique variables such as clamping position and pressure. These sources of error do not exist in the sensor data because there is no sample preparation. Uncertainty in sensor data is due to the short length scale of the measurement (5-10mm compared to 50mm for the Gurley test) combined with local variability (1-5mm length scale) in actual stiffness properties, and the tendency of the fibrous and otherwise non-homogeneous morphology of the sheet to distort the propagation of ultrasonic waves of similar lengths.

Given the three to four orders of magnitude difference between MD resolution of the Gurley test (~50mm) and the sensor measurement (200-1200m), and the fifth order of magnitude difference between the timescales of the measurements coupled with the viscoelasticity of paper, agreement between the CD stiffness profiles measured by these two methods is as good as can be expected, and is an indication that the stiffness profile does not change rapidly.

Comparison of Scanning Data with Single Point Measurements

The sensor can be used to measure stiffness in a non-scanning or "static" mode by holding the sensor stationary while making a complete FR measurement. This method has the advantage of relatively good single-measurement resolution in the MD (300m), and excellent CD resolution (~1mm), limited only by accuracy in knowledge of the sensor's CD position.

A CD profile can be constructed from a series of static mode measurements at various positions across the CD. The advantage of the static mode CD profile is nearly infinite CD resolution, but this advantage is obtained at the expense of a much poorer MD resolution for the entire profile. Much more time is needed in static than in scanning mode to get the data for entire profile. The static mode profile is constructed from measurements spanning of tens of kilometers (rather than approximately one kilometer in scan mode) of the web, even though the MD resolution of the individual measurements in static mode are much finer than in the scan mode. Comparisons of static to scanning mode CD profiles of CD and MD flexural rigidity are shown in Figures 6a and 6b respectively. In both figures, one scanning profile was measured immediately before half of the static data (CD position 0-175 inches) were measured. The second scanning profile was measured between after the first half of the static data and just before the second half of the static data were measured.

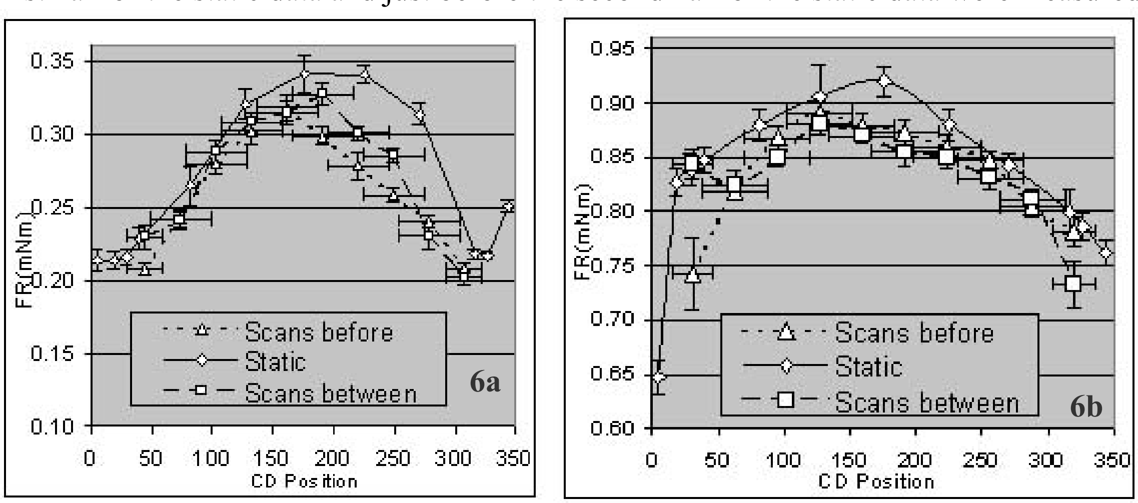

FIGURE 6. Comparisons of scanning with static CD profiles of CD(**a.**) and MD(**b.**) stiffness

The static and scanning profiles are in approximate agreement. The scanning profiles are mostly within experimental error (standard deviation of the mean of 16 scans) of each other, but differ by more than experimental error for about half of the data in the static profiles points (where vertical error bars represent standard deviation of the mean of 8 measurements) of both MD and CD stiffness. Whether this difference is due to genuine fluctuations in the stiffness profile or is unaccounted-for measurement error is yet to be determined.

SUMMARY

A compact, automated laser ultrasonic sensor for non-contact measurement of flexural rigidity of moving paper during manufacture was demonstrated on a papermaking machine during commercial operation. Comparisons of measurements of bending stiffness profiles by the sensor and by the traditional Gurley test are in reasonable agreement. Cross-direction stiffness profiles measured in scanning and static modes are also in approximate agreement.

The continuous monitoring of flexural rigidity on moving paper during manufacture that this sensor provides will allow control of the papermaking process to reduce stiffness variability and maximize stiffness while minimizing basis weight when desired, and reduce waste reprocessing costs. It is another step toward a paper manufacturing process that is more efficient and cost-effective in use of energy and natural resources.

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