DETERMINATION OF WOUND ROLL STRUCTURE USING ACOUSTIC TIME OF FLIGHT MEASUREMENT

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ABSTRACT

Roll structure measurement is presently done with destructive and intrusive measuring devices, such as FSR's or with specially instrumented winders. These methods are generally limited to research and development applications. Prior to this paper, there was no method of non-destructively determining the structure of a roll with unknown winding conditions.

This paper presents a measurement technique that uses thru thickness acoustic time of flight measurements to determine roll structure, an extension of the work done by J. David Pfeiffer [1] and alluded to by L. Eriksson [2] and D. R. Roisum [3]. A measurement is made of the time required for an acoustic wave to travel through the roll. This time of flight measurement is used as an extra degree of freedom in a winding model such as Z. Hakiel's [4] to replace an unknown or questionable model input, such as radial modulus or winding tension. The roll structure is determined by adjusting the model input until the calculated time of flight matches the measured time of flight.

The measurement technique was verified by comparison with two other independent methods. Each method was used to map the radial pressures in the left and right sides of six different wound rolls. Excellent results were obtained with the Acoustic Gage, when winding tension was used as the adjustable parameter. The excessive pressures predicted by winding models, the excellent results obtained by adjusting winding tension in the Acoustic Gage and the indication that stack tests produce accurate radial modulus data, cast doubt on the validity of the hoop stress boundary condition.

NOMENCLATURE

E_r = radial modulus, Pa (1 psi = 6.895 x 10^3 Pa)
C_1 = slope of the E_r vs. P curve, dimensionless

P = pressure, Pa (1 psi = 6.895×10^3 Pa)
c = wave propagation speed, m/s
E = modulus, Pa (1 psi = 6.895×10^3 Pa)
r = density Kg/m^3, (1 $lb/in.^3 = 3.613 \times 10^{-5}$ Kg/m^3)
V = velocity, m/s
t = time, s
l = length, m
T_w = winding stress, Pa (1 psi = 6.895×10^3 Pa)
T = stress, Pa (1 psi = 6.895×10^3 Pa)

BACKGROUND

Many common roll structure measurement techniques are qualitative not quantitative (capable of producing stress profiles in engineering units such as kPa or psi). Examples include the Rhometer, Schmidt Hammer or even a calibrated thumb. Most quantitative measurements are intrusive and destructive, such as FSR's and pull tabs. The remaining quantitative techniques, such as the density analyzer, require the rolls to be wound on special winders, with high precision measurement equipment. A very comprehensive discussion of roll structure measurement techniques is given by D.R. Roisum [3]. The roll structure measurement technique presented in this paper can be used to non-intrusively and non-destructively measure of stresses in a wound rolls.

STACK TESTS

When this work began, there were many questions about wave propagation and material properties that could best be answered in a flat rather than cylindrical geometry. These questions include: Can solid body wave mechanics be used with paper and plastic laminate structures? Can a transducer be coupled to paper and plastic laminates? Is the attenuation in paper and plastic laminate prohibitive for time of flight measurements? What are the material properties of a laminate structure?

Affect of Radial Pressure on Modulus and Density

Stack tests were preformed, using an Instron 8502, on an assortment of materials including papers and plastic films. The tests showed that the material density changed very little with pressure and therefore can be considered constant. The tests also showed that the radial modulus of a laminate could be modeled as a polynomial function of pressure. Most materials could be modeled using equation (1).

$$E_r = C_1 * P \qquad (1)$$

Speed of Sound

The theoretical speed of sound in a solid is given by equation (2), where E is Young's modulus for a bar (one dimensional longitudinal wave) or the bulk modulus for multi-dimensional waves [5]. The stack test data was used to determine the theoretical speed of sound, by replacing E with E_r and using a constant density r in equation (2).

$$c = \sqrt{\frac{E}{\rho}} \qquad (2)$$

The next step was to determine if this theory, based on solid body mechanics, would be valid for a laminate structure with variable modulus. An apparatus was made that allowed a wave to be initiated and observed as it passed two positions in the test stack under a known pressure. Two Kynar film strips were used as sensors, an oscilloscope was used for data collection and an analog amplifier/filter along with analytical techniques were used for signal processing. Initially the leading edges of the signals were used to determine the time of flight between the two sensors. This technique produced wave velocities well in excess of those predicted by equation (2). It was later determined that this technique is not valid due to the existence of forerunners [6]. Forerunners are small waves that travel ahead of the main energy packet, at speeds in excess of the group velocity. The best technique to measure wave speed, was to place the two sensors relatively close together and to use cross correlation to determine the time of flight. The sensors were placed relatively close to minimize the wave shape change due to frequency dependant velocity and attenuation. The decrease in accuracy caused by close spacing was more than offset by the accuracy increase from cross correlation. The results of this test showed that equation (2) is valid for a laminate structure with variable modulus. The test also gave insight, and forewarning, into the difficulties involved in time of flight measurements with low frequency, small bandwidth, waves traveling through highly attenuating non-linear materials.

Wave Generation and Reception

Initial efforts into wave generation and reception concentrated on commercial ultrasonic equipment typically used for non-destructive testing. This equipment is high frequency and wide bandwidth, which is advantageous for time of flight measurements. This equipment works very well on steel and composites, where coupling fluids and high contact pressures are not considered destructive or intrusive, but this is not the case with wound rolls. A test of a pair of Panametrics 13mm (.5 in.) 1 Mhz transducers showed that 175 kPa (25 psi) was required to dry couple a signal through a 10 mm (.38 in.) stack of polyester film. A frequency analysis of the received signal revealed that all the frequency components above 300 kHz had been completely attenuated. This test showed that excessive intrusive coupling pressure were required to transmit a signal through a web stack that is a small fraction of, the stack heights encounter in most wound rolls. The test also revealed that the bandwidth advantage of the commercial systems is nullified by the high frequency attenuation of the material. An attempt was then made to build a piezo pulsar that had approximately 100 time the energy of the commercial systems, but lacked the commercial systems bandwidth. This system was only a marginal improvement over the commercial systems. A pulsar with perhaps 10,000 times the energy of the commercial equipment is needed to initiate a wave capable of coupling to and traveling through a large roll. This pulsar must not only have very high energy, but must have bandwidth that will fully exploit the frequency transmission capability of the wound roll.

A mechanical pulsar was developed that released about 1 joule of energy in 3.3 ms (300 kHz), that translates to 300 kW of peak power. This was done by using a form of the Hopkinson pressure bar. A short bar (projectile) is shot, at known velocity, into a longer bar (pressure bar). A pressure wave, of magnitude described by equation (3), and duration equal to the time required for the wave to travel from the impact to the other end of the short bar and back, as described by equation (4). Figure 1 is a cross sectional view of the mechanical pulsar. The mechanical pulsar produces high frequency, wide bandwidth waves capable of traveling through very.

large rolls. To use the pulsar, tip the pulsar back allowing the projectile to slide to the inlet end of the tube. Press the pressure bar against the roll with very light spring pressure. Fire the pneumatic valve, causing the projectile to be shot into the pressure bar, initiating the wave. The air vents allow the projectile to travel at high velocity and prevents the pressure bar from acting as a pneumatic cylinder.

$$P = r\,c\,V \tag{3}$$

$$t = \frac{2 * l}{c} \tag{4}$$

Coupling and Attenuation

The attenuation in a laminate is very important to this project. A test was preformed to determine the signal attenuation thru both film and paper. The signal attenuation was determined by placing two sensors in a stack at several different pressures and distances and recording a wave as it passed. The attenuation, expressed in dB, was calculated as ten times the common logarithm of the ratio of peak signal strengths. The results of these tests were fit with a simple regression in equations (5) and (6).

$$\text{Paper} \quad dB\,/\,2.54\text{ cm (1 in.)} = -\,4.5 + .000002 * P \tag{5}$$

$$\text{Film} \quad dB\,/\,2.54\text{ cm (1 in.)} = -\,8.0 + .000003 * P \tag{6}$$

This attenuation is very high. At pressures commonly found in wound rolls the signal will lose more than half its strength for every 2.5 cm (1 in.) of travel.

ACOUSTIC ROLL STRUCTURE MEASUREMENT

The stack tests answered many questions about wave propagation through laminate structures. The tests also provided valuable information about wave generation, reception and signal processing. With these questions answered, the emphasis was then shifted from the stack to roll geometry.

Time of Flight Measurement

To determine the time of flight through the roll, the wave must be initiated and received at known times. Unlike the stack test, cross correlation cannot be used because of the extreme differences in wave shape between initiation to reception. A simple technique to determine the initiation time of the wave is to place a Kynar film sensor between the pulsar pressure bar and the roll. When the pulsar is fired, the Kynar produces a voltage signal as the wave travels from the pressure bar through the Kynar and into the roll. The signal from the Kynar sensor can go directly into an oscilloscope. This signal is very clean and has an amplitude of several volts. The scope is dc coupled and triggered at a level above the noise, but well below the peak amplitude of the signal. The actual trigger level is not important because of the extremely fast rise time of the signal. Recall that the total theoretical pulse duration is only 3.3 ms as compared to time of flights ranging from hundreds to thousands of microseconds.

The signal is received with a simple accelerometer or Kynar sensor hand held against the inside of the core. Again, this signal often requires very little amplification or filtering. The determination of the exact time the wave has been received is very difficult because of the low frequency and small bandwidth of the wave. Many references were consulted about this problem. There are several references discussing the problem, but a satisfactory solution was not found in the literature. The stack tests showed that the leading edge of the wave cannot be used because of the forerunners. The technique that worked best was to pick the first peak that was at least 5 standard deviations above the signal noise. In all the cases tested, this algorithm produced very reasonable time of flight values. Figure 2 shows several examples of normalized signals and time of flight measurements used in the Appendix.

Determination of Roll Structure

The time of flight measurement is an extra degree of freedom (redundant or indeterminate constraint) that can be used in a winding model such as Hakiel's to replace and unknown or questionable model input, such as winding tension, or radial modulus. An example of it's use is the determination of the roll structure of an arbitrary roll from the warehouse. All the input needed to model this roll could be determined except for the winding tension. A guess could be made of the winding tension and the roll modeled. The model will produce a pressure profile that can be used with equations (1) and (2) to determine the speed of sound as a function of radius. The speed of sound as a function of radius can be integrated from core to the outside of the roll to determine what time of flight that would result from that initial guess of winding tension. The difference between the calculated time of flight and the actual measured time of flight is then used to make a better guess at the winding tension. This iteration process is continued until the calculated time of flight converges with the actual measured time of flight. The data from the last iteration is the roll structure. This method is called the Acoustic Roll Structure Gage.

Another potential unknown or questionable model input is radial modulus. The time of flight measurement can be used with equation (2) to determine the average radial modulus. This constant modulus can be used in a model such as Altmann [7], Yagoda [8] or Hakiel to determine roll structure. This method is called the Constant E_r Roll Structure Gage.

A computer program was written that reads the two signals from an oscilloscope. These two signals are processed, according to the criterion discussed earlier, to determine the measured time of flight. The program has two options Constant E_r and Acoustic Gage. If the Constant E_r option is selected, the time of flight measurement is used to calculate and average E_r , which is used in the model to replace the stack test E_r function. The remaining model inputs, including T_w remain unchanged. The program then calculates the roll structure, plots the radial pressure distribution and files the data. If the Acoustic Gage option is invoked, an initial guess of T_w and the stack test E_r function is used to calculate the roll structure. This radial pressure and equations (1) and (2) are integrated to determine the calculated time of flight. The error between the measured time of flight and the calculated time of flight is used to make a better guess at T_w. This iteration process continues until the difference between the measured and calculated time of flight is less than 1 ms. The roll structure data from the last iteration is plotted and the data written to a file. Figure 3. is a screen dump of the Acoustic Gage program used to determine the roll structure of "Roll #1 RIGHT" in the Appendix.

Verification

The acoustic measurement techniques were verified by comparison with two independent measurement methods FSR's and pull tabs. The two direct pressure measurement methods and the two acoustic techniques were used to map the radial pressures in the left and right sides of six different wound rolls. The results of these measurements along with Hakiel's model output are given in the Appendix. Excellent results were obtained with the Acoustic Gage, when winding tension was used as the adjustable parameter. When the average radial modulus, determined with time of flight measurements, was substituted for the stack test data the resulting radial pressure profile was often very similar to the original Hakiel's model output. This suggests that the radial modulus determined with stack tests is probably accurate. The excessive pressures predicted by winding models, the excellent results obtained by adjusting winding tension in the Acoustic Gage and the indication that stack tests produce accurate radial modulus data, cast doubt on the validity of the hoop stress boundary condition

Hoop Stress Boundary Condition

Four different models were used to calculate the expected radial pressure for these rolls. The model input parameters were carefully measured and independently verified. Except for the core area, all the models predicted very similar results. The pressures predicted by all the models were considerably higher than the actual pressure measured with three independent techniques FSR's, pull tabs and the Acoustic Gage. These models all use the same outer boundary condition, the hoop stress equation (7).

$$P = \frac{T_w * h}{r} \tag{7}$$

This equation assumes no shear stresses and does not account for such factors as air entrainment. A simple modification, to make this boundary condition more realistic, is to use some value T in place of T_w, such that $T < T_w$. The Acoustic Gage uses the extra degree of freedom from the time of flight measurement in place of T_w and iterates to find a value T that is more reasonable.

RESULTS AND CONCLUSION

A new roll structure evaluation tool has been developed. This measurement technique uses time of flight measurements and existing winding models to determine roll structure. This method has several advantages over existing roll structure evaluation tools. These advantages include being non-destructive and non-intrusive and does not require knowledge of the winding conditions.

Stack tests were done to determine material properties and confirm that solid body wave mechanics could be used to describe waves in laminates. A mechanical pulsar was developed that can generate a high energy, wide bandwidth wave in a wound roll. A time of flight measurement method was also developed. These components, including an existing winding model, were integrated into an algorithm to determine roll structure. This system is called the Acoustic Gage.

The Acoustic Gage results agreed with two other independent roll structure measurement tools, all of which were much lower than predicted by winding models. The results cast doubt on the validity of the hoop stress equation as an outer boundary condition for wound roll models.

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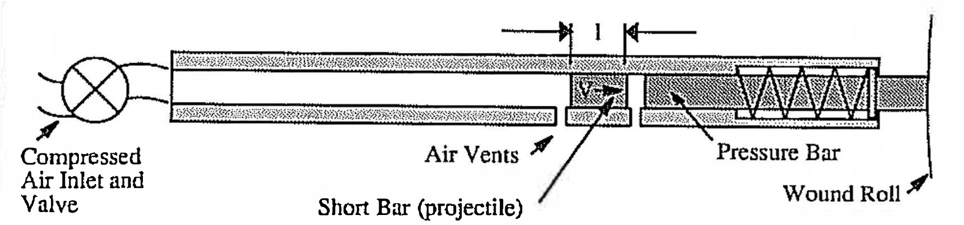


Fig. 1 Mechanical Pulsar

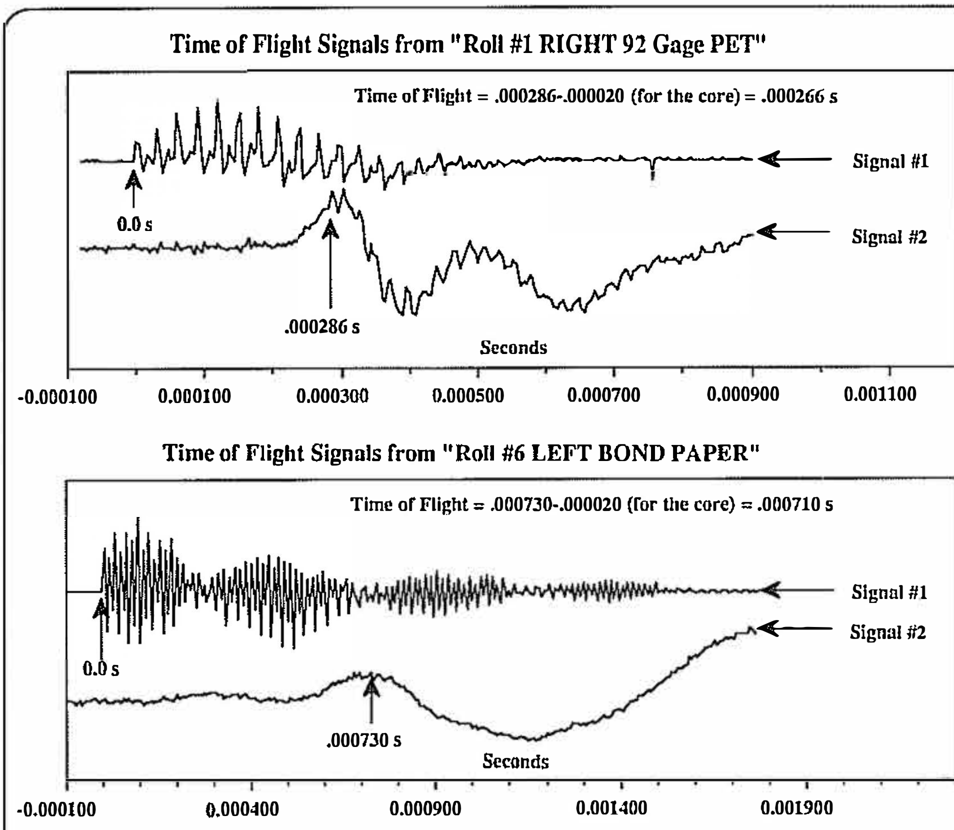


Fig. 2 Time of Flight Measurement Examples

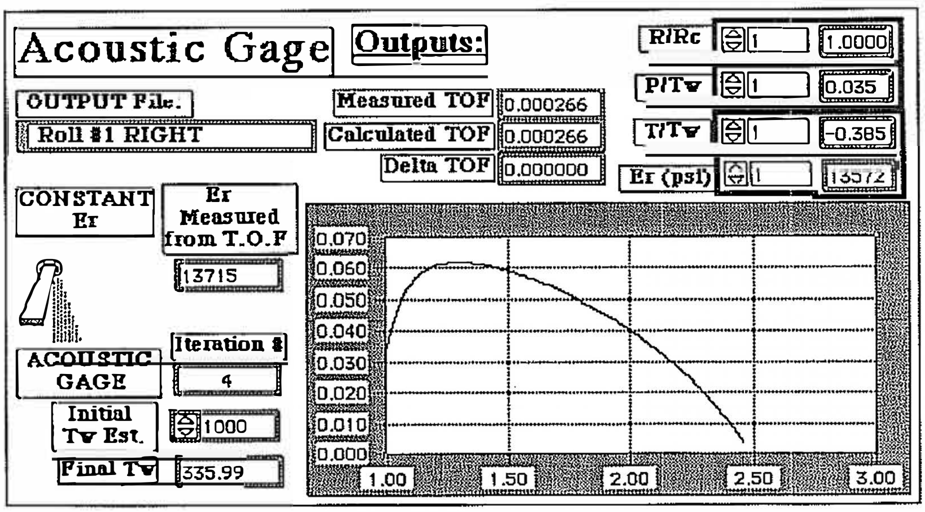
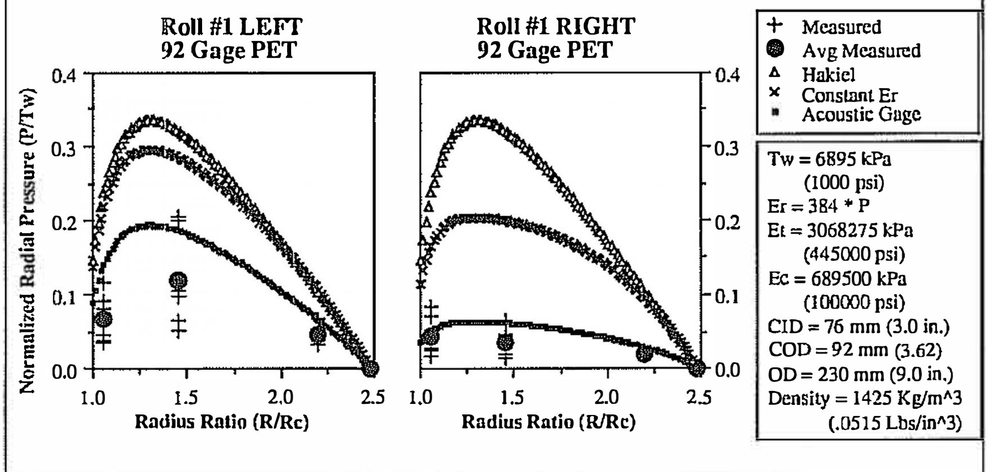
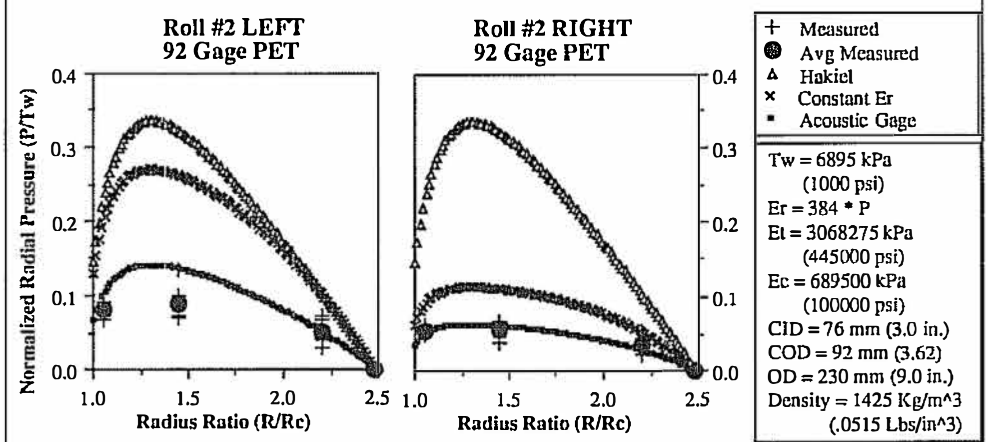
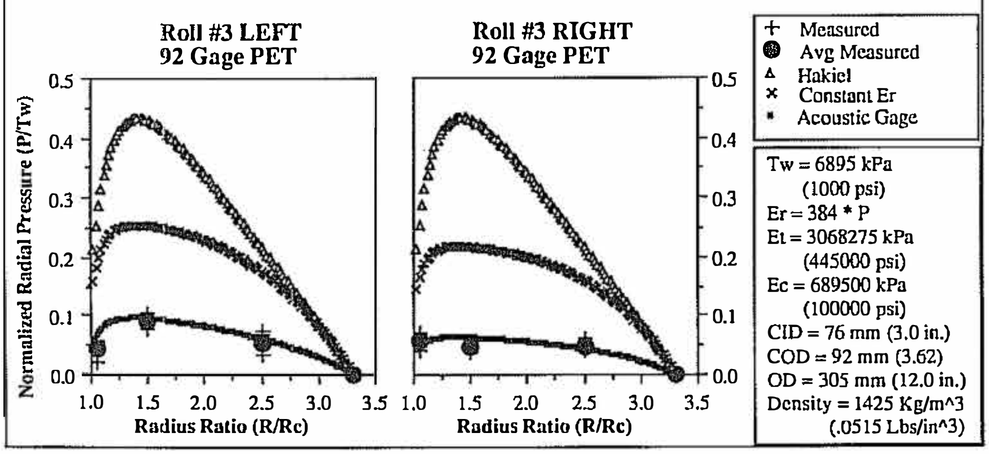
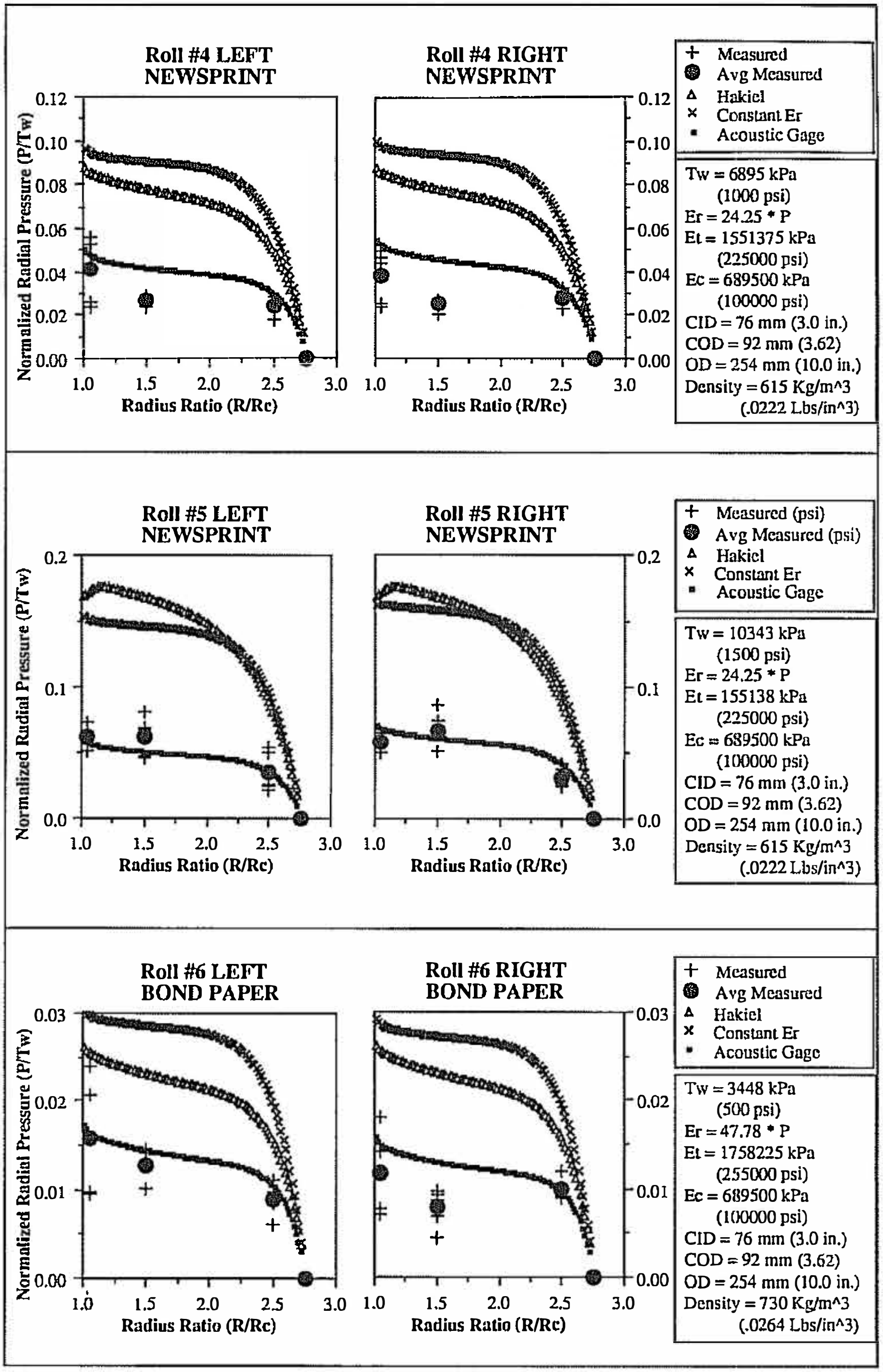


Fig. 3 Acoustic Gage Program Screen


Roll #1 LEFT
92 Gage PET
Roll #1 RIGHT
92 Gage PET
Normalized Radial Pressure (P/Tw)
Radius Ratio (R/Rc)
Measured
Avg Measured
Hakiel
Constant Er
Acoustic Gage
Tw = 6895 kPa
(1000 psi)
Er = 384 * P
Et = 3068275 kPa
(445000 psi)
Ec = 689500 kPa
(100000 psi)
CID = 76 mm (3.0 in.)
COD = 92 mm (3.62)
OD = 230 mm (9.0 in.)
Density = 1425 Kg/m^3
(.0515 Lbs/in^3)


Roll #2 LEFT
92 Gage PET
Roll #2 RIGHT
92 Gage PET
Normalized Radial Pressure (P/Tw)
Radius Ratio (R/Rc)
Measured
Avg Measured
Hakiel
Constant Er
Acoustic Gage
Tw = 6895 kPa
(1000 psi)
Er = 384 * P
Et = 3068275 kPa
(445000 psi)
Ec = 689500 kPa
(100000 psi)
CID = 76 mm (3.0 in.)
COD = 92 mm (3.62)
OD = 230 mm (9.0 in.)
Density = 1425 Kg/m^3
(.0515 Lbs/in^3)


Roll #3 LEFT
92 Gage PET
Roll #3 RIGHT
92 Gage PET
Normalized Radial Pressure (P/Tw)
Radius Ratio (R/Rc)
Measured
Avg Measured
Hakiel
Constant Er
Acoustic Gage
Tw = 6895 kPa
(1000 psi)
Er = 384 * P
Et = 3068275 kPa
(445000 psi)
Ec = 689500 kPa
(100000 psi)
CID = 76 mm (3.0 in.)
COD = 92 mm (3.62)
OD = 305 mm (12.0 in.)
Density = 1425 Kg/m^3
(.0515 Lbs/in^3)



Roll #4 LEFT NEWSPRINT
Roll #4 RIGHT NEWSPRINT
Normalized Radial Pressure (P/Tw)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1.0 1.5 2.0 2.5 3.0
Radius Ratio (R/Rc)
Measured
Avg Measured
Hakiel
Constant Er
Acoustic Gage
Tw = 6895 kPa (1000 psi)
Er = 24.25 * P
Et = 1551375 kPa (225000 psi)
Ec = 689500 kPa (100000 psi)
CID = 76 mm (3.0 in.)
COD = 92 mm (3.62)
OD = 254 mm (10.0 in.)
Density = 615 Kg/m^3 (.0222 Lbs/in^3)
Roll #5 LEFT NEWSPRINT
Roll #5 RIGHT NEWSPRINT
0.2
0.1
0.0
Measured (psi)
Avg Measured (psi)
Hakiel
Constant Er
Acoustic Gage
Tw = 10343 kPa (1500 psi)
Er = 24.25 * P
Et = 155138 kPa (225000 psi)
Ec = 689500 kPa (100000 psi)
CID = 76 mm (3.0 in.)
COD = 92 mm (3.62)
OD = 254 mm (10.0 in.)
Density = 615 Kg/m^3 (.0222 Lbs/in^3)
Roll #6 LEFT BOND PAPER
Roll #6 RIGHT BOND PAPER
0.03
0.02
0.01
0.00
Measured
Avg Measured
Hakiel
Constant Er
Acoustic Gage
Tw = 3448 kPa (500 psi)
Er = 47.78 * P
Et = 1758225 kPa (255000 psi)
Ec = 689500 kPa (100000 psi)
CID = 76 mm (3.0 in.)
COD = 92 mm (3.62)
OD = 254 mm (10.0 in.)
Density = 730 Kg/m^3 (.0264 Lbs/in^3)

DETERMINATION OF WOUND ROLL STRUCTURE USING ACOUSTIC TIME OF FLIGHT MEASUREMENT
Ron Swanson

1. How do you deal with radial winding tension variations in your "acoustic gauge" computation?
Zig Hakiel, Eastman Kodak

The thru thickness acoustic gage measures time of flight (one degree of freedom). Therefore only one unknown can be determined, i.e., if winding tension is unknown the profile such as constant torque or constant tension must be known. If both are unknown, multiple time of flight measurements must be done. (Pfeiffer '66)

2. When making time of flight measurements how are the accelerometers attached to the roll cores?
Cornelius Bailey, Bureau of Engraving & Printing

The accelerometer can be held by hand or in a fixture that is isolated from the pulser.

3. How do you determine E_r for a roll you get handed to you "off the shelf"? Isn't E_r a function of wound in tension?
John Staples, Sonoco Products Co.

You must know the E_r as a function of pressure. If the "off the shelf roll" is of a known material such as polyester the function will be about 200-400 times the pressure in psi. If the material is paper it will be about 50-100 times the pressure in psi. Rough estimates will give very reasonable pressure profiles. If the material is totally unknown, take the time of flight measurements first, then slab the roll and do a stack test.