ENTRAINED AIR FILMS IN CENTER WOUND ROLLS - WITH AND WITHOUT THE NIP

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ABSTRACT

Development of analytical expressions predicting the thickness of fluid layers in the area of a foil bearing has been ongoing for nearly forty years. These expressions have been adapted to include air as the lubricating medium for use in predicting layer separation in wound rolls or for predicting the floating height of a web over a roller. An experimental technique has been perfected to study the air entrainment in wound rolls of web material. This paper will focus on providing proof regarding what expressions should be employed and how they are used to model the amount of air which is entrained in centerwinding, with or without an impinging nip.

NOMENCLATURE

b	half width of contact
b_w	unit width
E_{nip}	Young's modulus of the nip
E_r	Young's modulus of the wound roll, radial direction
E', E^*	equivalent (combined) modulus
F	nip load per unit width
G	material parameter, dimensionless
h_o	minimum air film thickness
L	nip load per unit width
P_{atm}	atmospheric pressure
P_o	pressure beneath the outer layer of the winding roll, T/s

P_{max} maximum pressure in contact zone

r_e equivalent (combined) radius

r_{nip} nip radius

s outer radius of winding roll

T web tension per unit width

U, U' velocity parameter, dimensionless

V web line velocity

W, W' nip load parameter, dimensionless

η dynamic viscosity of air, $3.077*10^{-7}$ N-min/m^2 @ 27°C

σ web surface roughness, r.m.s.

σ_r radial pressure in wound roll

ν_{nip} Poisson's ratio for the nip or rider roll

ν_r Poisson's ratio for the wound roll

INTRODUCTION

Technologies that have been previously tested for measuring the air layer thickness in a wound roll have met with limited success. Good and Holmberg [1] note successful measurements as long as air layers remain large compared to the radial runout on the surface of the roll being tested. Bouquerel and Bourgin [2] show some success with the on line density method of measurement although the data does not appear to be in agreement with theory over the full range of the tests that were run. Good and Covell [3] introduce a novel concept for measuring total air volume with the wound roll bubblerimeter. This technique gives consistent results for air volumes in wound rolls immediately after winding but lacks the ability to account for the air escaping, due to side leakage, during the winding process. At the Web Handling Research Center we have employed an alteration to the winding process in conjunction with the wound roll bubblerimeter in order to measure the total volume of air entrained during the winding process. During the film winding process the rolls are edge sealed to prohibit the escape of entrained air. The rolls are then unwound under water collecting all entrained air in a graduated cylinder. A comparison between the measured air layers and those predicted by existing models for center winding with and without a nip roller is presented here.

MODELS PREDICTING AIR LAYER DEVELOPMENT

Blok and vanRossum [4] introduced the concept of a foil bearing in 1953. They define a foil bearing as an extremely flexible foil stretched around half the circumference of a journal. Experiments are then carried out to verify the coefficient of friction for the foil bearing with oil as the lubricating medium. Knox and Sweeney [5] expanded the work done by Blok and vanRossum to include air as the lubricating medium. Air film thickness was inferred experimentally by using a knowledge of film surface roughness in conjunction with measurements of the coefficient of friction between the film and a roller. Equation 1, which is taken from the work done by Knox and Sweeney, is used to predict the air layer that is developed during center winding.

$$h_{o,cw} = 0.65s\left[\frac{12\eta V}{T}\right]^{\frac{2}{3}} \tag{1}$$

Good and Holmberg [1] carried the air film work another step further by experimentally verifying that the foil bearing relationship applied to center wound rolls of web material. In this work the air film thickness was measured directly at the outer layer during winding. This work provides satisfactory evidence to indicate that the air layer development for centerwound film rolls is well described by Equation (1).

Three different expressions describing air layer development in the presence of a force loaded layon roll will be considered here. Bertram and Eshel [6] derive an expression for the air layer developed under a force loaded nip by solving the Reynolds equation for an incompressible fluid. The work was primarily concerned with interlayer pressures and wound roll slippage, so direct verification of air layer thickness was not reported. The expression relating nip load to air film thickness is given as:

$$L = 4\eta V\frac{r_e}{h_o} + \frac{4}{3\pi}\frac{T\sqrt{2r_e h_o}}{s} \tag{2}$$

Good and Covell [3] note the second term is negligible and reduce the equation to an explicit solution for the air layer thickness which is given as Equation 3. In (3) it is assumed that the nip load is independent of web line tension.

$$h_{o,nip} \approx \frac{4\eta V r_e}{L} \tag{3}$$

Hamrock and Dowson [7] develop an elastohydrodynamic expression to calculate the film thickness between two surfaces in which the contact geometry would be considered elliptical in shape. This work is intended for use in bearing lubrication with lubricants much more viscous than air. In the development a geometry parameter is used which will allow for rectangular contact. Rectangular contact most closely approximates the nip loaded wound roll configuration. Parameters are combined in dimensionless groups representing load, speed, and material effects on the air film thickness. A simultaneous solution to the Reynolds and elasticity equations is then carried out numerically. A curve fit of the numerical solutions is supplied for a range of values in the dimensionless parameters. Equations 4 through 9 are taken from the work by Hamrock and Dowson, some subscripts have been changed to follow the nomenclature herein. For the condition of rectangular contact and "soft" materials Hamrock and Dowson determined the minimum air film thickness to be:

$$h_o = r_e 7.32 U^{0.64} W^{-0.22} \tag{4}$$

Where a speed parameter is defined as:

$$U = \frac{\eta V}{E' r_e} \quad (5)$$

and an equivalent radius is developed as:

$$\frac{1}{r_e} = \frac{1}{s} + \frac{1}{r_{nip}} \quad (6)$$

and an average velocity is defined as:

$$V = \frac{V_{nip} + V_{roll}}{2} \quad (7)$$

A load parameter is developed as:

$$W = \frac{F}{E' r_e} \quad (8)$$

and an equivalent modulus is defined as:

$$E' = \frac{2}{\frac{1-\nu_r^2}{E_r} + \frac{1-\nu_{nip}^2}{E_{nip}}} \quad (9)$$

The curve fit solution applies over a range of U and W from $5.14*10^{-9}$ - $5.14*10^{-8}$ and $2.2*10^{-4}$ - $2.2*10^{-3}$ respectively. Typical film winding parameters would require an extension of the speed parameter down to $1*10^{-11}$.

Chang, Chambers, and Shelton [8] develop an elastohydrodynamic equation for nip loaded air film thickness following the work of Hamrock and Dowson specifically for the case of rectangular contact. The new solution is developed for an expanded range of dimensionless parameter values to encompass the materials, lubricants and elastomeric nips typically encountered in winding. The results yield closed form solutions for the air film height, h_o, in the central nip region and for the decompressed value after expansion to atmospheric pressure. As before the dimensionless parameter groupings are employed in a numerical solution to the Reynolds and elasticity equations with subsequent curve fit solutions. Chang et al found that a single curve did not well represent the air film thickness over the range of material parameters studied. Thus for effective moduli between 4.8 Mpa and 34.47 Mpa:

$$h_{o,nip} = r_e 8.5 U'^{0.72} W'^{-0.5} G^{-0.48} \tag{10}$$

$$h_{c,nip} = r_e 12.5 U'^{0.71} W'^{-0.2} G^{-0.23} \tag{11}$$

and for effective moduli between 0.69 Mpa and 4.8 Mpa:

$$h_{o,nip} = r_e 4.8 U'^{0.66} W'^{-0.35} G^{-0.47} \tag{12}$$

$$h_{c,nip} = r_e 7.4 U'^{0.66} W'^{-0.21} G^{-0.33} \tag{13}$$

Where U' and W' are defined differently from Hamrock and Dowson as:

$$U' = \frac{\eta V}{P_{atm} r_e} \tag{14}$$

$$W' = \frac{F}{P_{atm} r_e} \tag{15}$$

A nondimensional material parameter is introduced as:

$$G = \frac{E^*}{P_{atm}} \tag{16}$$

where

$$E^* = \frac{1}{\dfrac{1-\nu_r^2}{E_r} + \dfrac{1-\nu_{nip}^2}{E_{nip}}} \tag{17}$$

The c subscript represents the air layer corrected for expansion back to atmospheric pressure. Chang et al have curve fit for a range of U' and W' covering typical winding parameters from $5.9*10^{-9}$ - $7.36*10^{-8}$ and $3.0*10^{-3}$ - $1.42*10^{-1}$ respectively.

A comparison between the three air layer prediction algorithms (3), (4), and (12) is shown in Figure 1. A second comparison is shown in Figure 2 where the prediction by Hamrock and Dowson can be seen to lie between Chang, Chambers and Sheltons' predictions for wound on air layer and the air layer corrected for expansion to atmospheric pressure. Note the reasonable values given by the equations from Hamrock and Dowson even though they are being used outside the specified range of nondimensional parameters.

Use of the elasto-hydrodynamic solutions in winding requires the selection of a radial modulus for the wound roll in the vicinity of the nip contact area. This can be accomplished using an iterative process involving calculations of air film compression and half width of contact. An equation for the radial modulus of air separated film layers from Good and Covell [3] is given as:

$$E_{r,air} = \frac{(\sigma_r + P_o + P_{atm})^2}{P_o + P_{atm}} \qquad (18)$$

The iterative process begins by selecting an initial estimate for the radial modulus to use with the selected speed, roll radius, and nip load. These values are used with equations (12) and (13) to compute the central zone air film layer thickness and the expanded air layer thickness. These air layers represent the compression of air in the wound roll outer layers. P_o in (18) can now be solved as the atmospheric pressure times the compression predicted with (12) and (13). The Hertzian contact expressions[11] are employed to determine the half width of contact and the maximum pressure as:

$$b = \sqrt{\frac{2L[(1-\nu_{nip}^2)/E_{nip} + (1-\nu_r^2)/E_r]}{\pi(\frac{1}{2r_{nip}} + \frac{1}{2s})}} \qquad (19)$$

$$P_{\max} = \frac{2L}{\pi b} \qquad (20)$$

P_{max} is used as the radial stress in (18). These computed values are used to solve (18) for the radial modulus. This value of radial modulus is used as the initial estimate for the second pass through the process. When the estimate and final computed value for radial modulus converge the iteration process is complete. A flow chart for this process is given as figure 3.

EXPERIMENTAL METHOD

In order to measure the total volume of air entrained during the wind, a fixture has been constructed to seal the edges of the roll during winding. This is accomplished by spraying a small stream of melted paraffin wax on the edges of the roll as it is wound. The melted wax will solidify shortly after making contact with the room temperature film roll, thereby preventing air escape to side leakage. An analysis of the initial air layer decay rate will suggest a need to apply the wax stream at the oncoming film layer as close to the tangent point as possible. A squeeze film relationship taken from Blevins [9] follows.

$$t = \frac{\eta b_W L^3}{2W}\left(\frac{1}{h_2^2} - \frac{1}{h_1^2}\right) \tag{21}$$

If center winding conditions are assumed with a roll radius of 0.053 m, winding tension of 87.6 N/m, and a velocity of 91.44 m/min, then (1) can be used to compute the initial air layer of 8.5 μm. Applying (21) to the above winding conditions will show the air layer decays to 7.6 μm in 2.4 seconds. This represents a 10% reduction in air layer thickness in as few as 10 rotations of the winding roll. To allow the wax stream to be applied at the outer layer, while protecting the roll surface from overspray, the outer 1.2 cm of each edge of the roll is treated as waste material. This waste edge is used as a backstop for the wax spray and removed by a slitter 1/2 rotation later. Figures 4 and 5 are pictures of the wax application and slit edge removal fixture. After winding, the edge sealed roll is unwound in the bubblerimeter. In this process the rolls are unwound under water. The air that is released by the sealed roll is collected by a fluid filled graduated cylinder which sets above an inverted funnel (see Figure 6). This collected volume of air is assumed to be the total air entrained during the winding process. The measured air volume is then compared to an analytically derived air volume or divided by the total film surface area to arrive at an average air layer thickness. The winding experiments presented in this work were carried out on films which possess a characteristically low irreducible air volume. Irreducible air volume is that air which exists in the void space between asperities with two film surfaces in contact. This tare air can be computed from knowledge of film surface roughness as shown in Equation 22 [10].

$$\text{Tare} = 3\sqrt{2}\sigma * \text{(Film Surface Area)} \tag{22}$$

This equation is valid only for films with like frontside and backside surface roughness. This concept was tested for two ICI films with largely different surface character. The two films were wound at very low speed and moderate tension in an effort to avoid air entrainment while not generating significant asperity deformation. A sample of ICI 442 film with 91.44 m of length and 15.24 cm of width was wound. When unwound it released 1 ml of air. This compares favorably with a computed value of 0.41 ml from a 6.92 nm rms surface roughness. A sample of ICI 377 film with 82.3 m of length and 15.24 cm of width was wound. When unwound it released 77 ml of air. This also compares favorably with a computed value of 75 ml from a 1415 nm rms surface roughness. All air volume measurements that have been taken with the bubblerimiter have been reduced by 3% to account for the vacuum expansion created by the water head.

EXPERIMENTAL RESULTS

Center wound rolls were edge sealed for 5 sets of winding conditions. Figure 7 shows the measured average air layer plotted with the prediction from equation (1). The edge sealing process is most effective for smaller air layers. The roll deformation that occurs as pressure builds near the core can lead to failure of the wax seal after it has solidified. This seal failure is evident for the point taken at 60.96 m/min with 87.56 N/m tension. The other 4 points are in good agreement with the analytical prediction. Nine sets of winding conditions were run for the nip loaded centerwinding configuration. Figures 8, 9, and 10 show the experimental points plotted with the prediction algorithm from Chang, Chambers, and Shelton [8]. The plots for nip loads of 875.6 N/m and 1400.9 N/m show very good agreement between theory and experiment. The 525.3 N/m case is believed to be somewhat influenced by stiction in the piston driving the nip roller. Equation (13) was used to generate the theoretical curves in figures 8, 9, and 10 with an elastic modulus input of 0.689 Mpa, which is the lowest modulus value allowed in the curve fit equation. Figure 11 is a table showing the radial modulus that was computed for the nine sets of winding conditions. The computations were made using the iterative process previously described.

CONCLUSION

As expected, the centerwinding experiments appear to be well described by the expression taken from the work of Knox and Sweeney [5]. Using the centerwinding case as a proving ground for the edge sealing process generates confidence that the air layer developed in the presence of a force loaded rider roller is well described by the work of Chang, Chambers, and Shelton [8].

ACKNOWLEDGEMENTS

This publication is a result of research which was funded by the Web Handling Research Center of Oklahoma State University. The authors would like to thank the sponsors of the WHRC for supporting this research.

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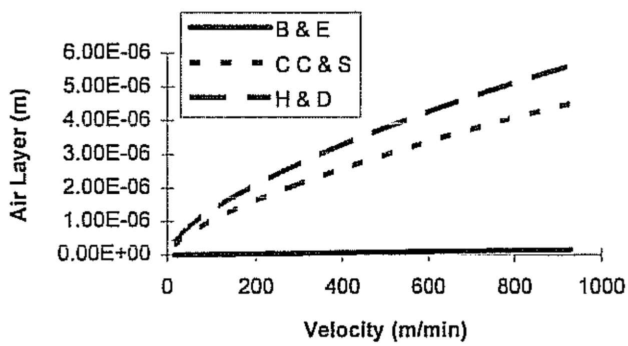

Figure 1 - Comparison of nip loaded air layer expressions (3), (4), and (12)

r_{nip} = 0.102 m, s = 0.254 m, L = 525 N/m, E_r = 0.689 Mpa

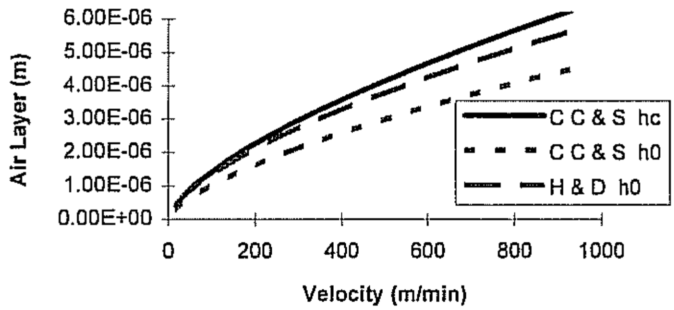

Figure 2 - Comparison of nip loaded air layer expressions (4), (12), and (13)

$r_{nip} = 0.102$ m, $s = 0.254$ m, $L = 525$ N/m, $E_r = 0.689$ Mpa

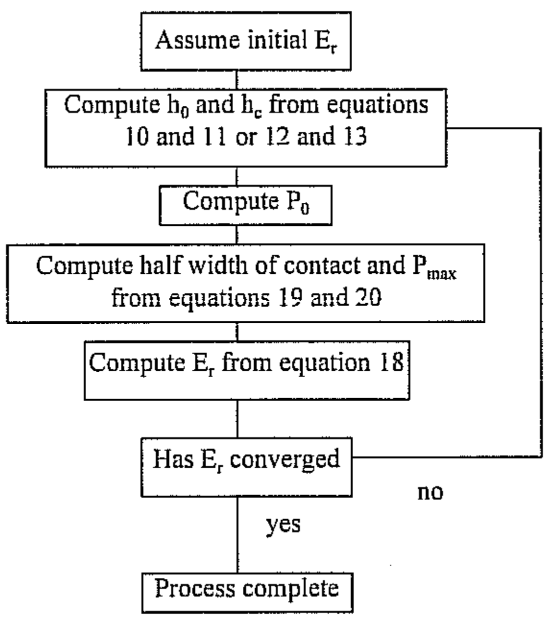

Figure 3 - Flow chart for E_r computation

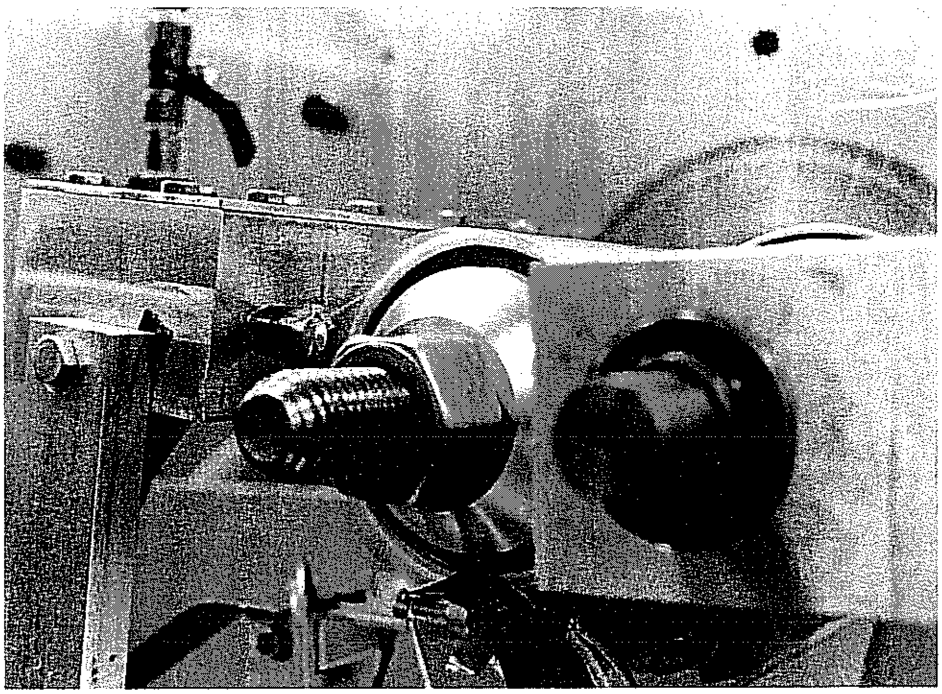

Figure 4 - Wax application and edge removal fixture

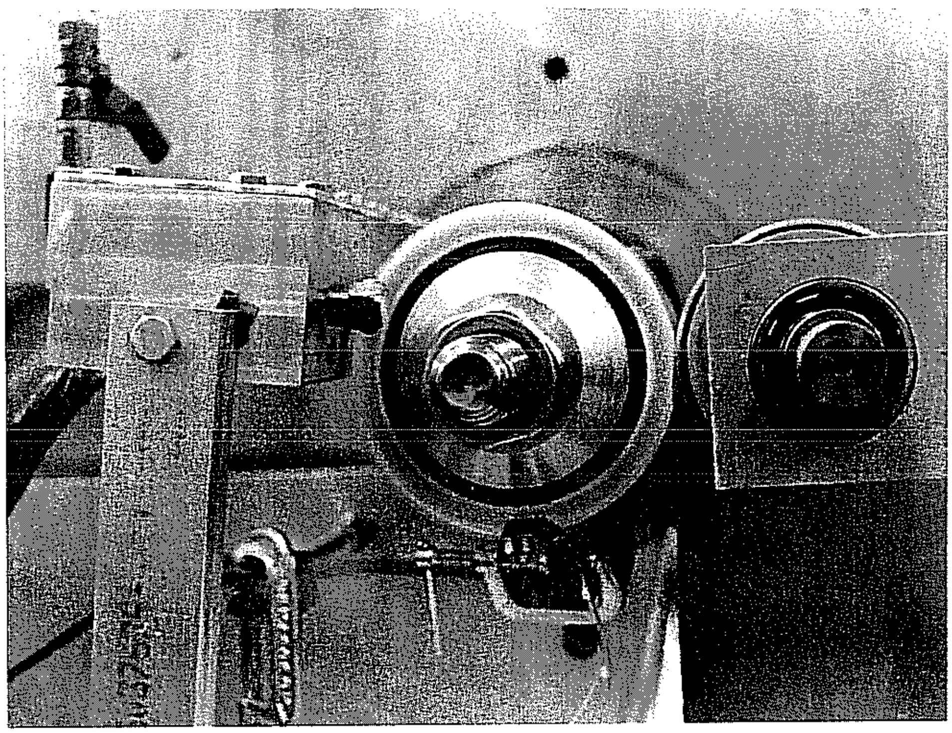

Figure 5 - Wax application and edge removal fixture

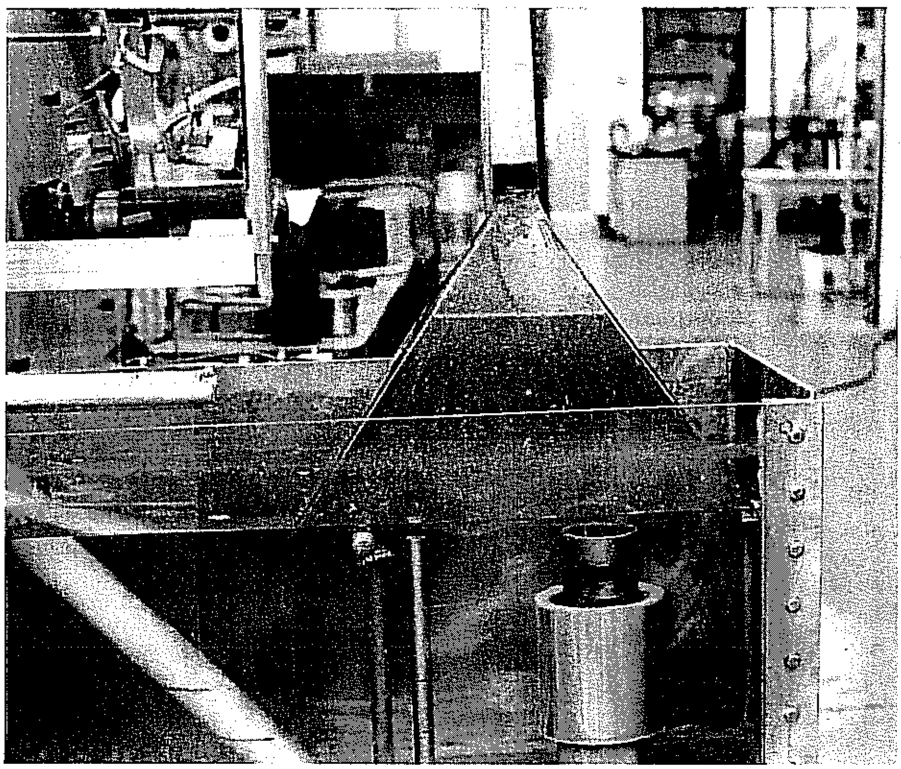

Figure 6 - Wound roll Bubblerimeter

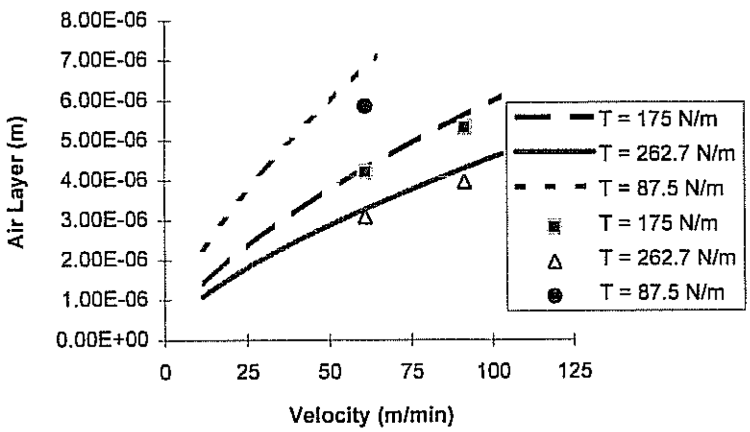

Figure 7 - Centerwinding air layer data

$s_{avg} = 0.057$ m

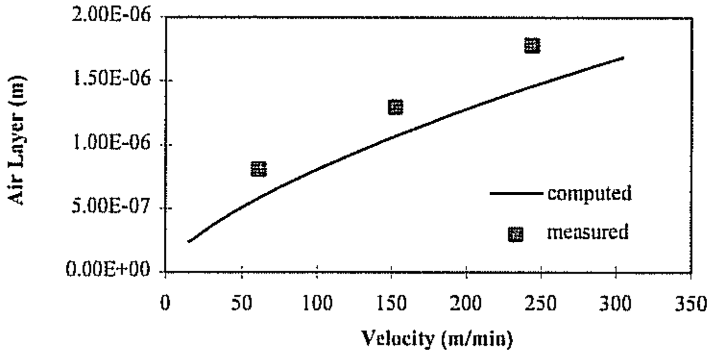

Figure 8 - Nip loaded air layer data

L = 525.3 N/m, s_{avg} = 0.057 m, r_{nip} = 0.051 m, E_r = 0.689 Mpa

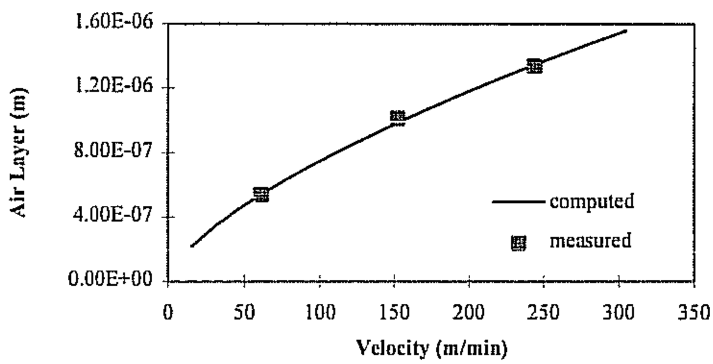

Figure 9 - Nip loaded air layer data

L = 876.6 N/m, s_{avg} = 0.057 m, r_{nip} = 0.051 m, E_r = 0.689 Mpa

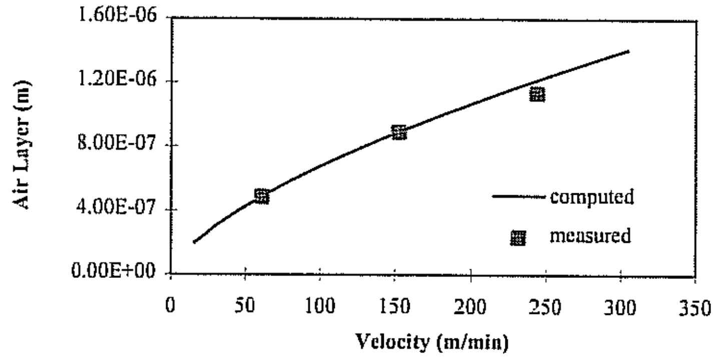

Figure 10 - Nip loaded air layer data

L = 1400.9 N/m, s_{avg} = 0.057 m, r_{nip} = 0.051 m, E_r = 0.689 Mpa

	L = 525.3 (N/m)	L = 876.6 (N/m)	L = 1400.9 (N/m)
V = 60.96 (m/min)	0.40 Mpa	0.43 Mpa	0.55 Mpa
V = 152.4 (m/min)	0.40 Mpa	0.43 Mpa	0.55 Mpa
V = 243.84 (m/min)	0.40 Mpa	0.43 Mpa	0.55 Mpa

Figure 11 - Computed radial modulus for nip loaded winding experiments

Question - I see you applied the Hertzian Contact Theory. We all know that only applies to linear theory. Do you have any comments on how this assumption works for you.

Answer - No comment. It was a simple calculation that was easy for all engineers to use. So, yes I agree, there would be better ways to approach this for exactness for that particular problem. But it seems this supplies an adequate solution.

Question - I just wanted to ask, you showed us some graphs of air layer thickness from the bubblerimeter experiment, correct? Does that include the Tare Air?

Answer - In the paper we have excluded Tare Air and another exclusion we make is 3% air expansion because we lift the water above the unwinding roll. And if you notice, I used ICI 442 Film in all of these experiments so that my Tare Air was almost negligible anyway.

Question - So it is a small fraction of it any way.

Answer - Yes

Question - What would you suggest for improvements on the elastohydrodynamic model

Answer - To improve the model? The allowable lower radial modulus.

Question - Air layers are a function of time. The radial modulus is a function of the air layer. Can this be handled in a typical winding model? I'd like your comments.

Answer – Absolutely, in fact, if you look at the decay in radial modulus is a function of the pressure from the air layer and pressure is a function of time.

Question - From what I understood the concept of irreducible volume is a way to describe roughness. Is that right?

Answer - Yes

Question - The only way to discriminate between two different topographies. In other words with the same ultimate volume between a few high peaks and very smooth surfaces lot of small peaks displayed in the surface in both case they have the same irreducible air volume.

Answer - It won't discriminate. What I was after there was a means of quantifying the how much air was there.

Question - Do you think that two films quite different but having the same ultimate air volume would it be possible?

Answer - The square root of 2 times Rq assumes that similar surfaces were coming into the contact. If you replace that Square root of 2 times Rq factor with the square root of the sum of the squares of Rq for the two surfaces you will find that it works quite well.