AIR FILMS BETWEEN A MOVING TENSIONED WEB AND A STATIONARY SUPPORT CYLINDER

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ABSTRACT

Web quality and web processing efficiency depend upon maintaining a proper lubricating air film between the moving web and the driving and supporting rollers. As web line speeds are increased, the film can become too thick, reducing traction between the web and roller. A common means to improve traction when this "web flotation" is encountered is to roughen the roller surface. While flexible foil bearing theory may be applied to predict the thickness of the air film between a non-porous web and a smooth roller, empiricism must be applied for textured, roughened rollers. The mechanisms through which these surfaces work have been unclear and models to predict their performance have been unavailable. This paper presents the results of research conducted to identify the traction improvement mechanism through measurements of the air film thickness between a web and roughened rollers. The principle objective of this work was to determine how the addition of surface roughness changes the air film from that which can be predicted with foil bearing theory.

The effects of surface roughness on the air film were evaluated experimentally by measuring the height of a tensioned smooth web moving over a stationary cylinder with three alternate surface roughness segments. The 152 mm (6 inch) wide web was a spliced continuous loop of 36 μm (1.4E-03 inch) thick polypropylene with vacuum deposited aluminum on the upper surface. The stationary cylinder was aluminum with a diameter of 203 mm (8 inches) and alternate surface roughness segments of 0.76, 2.0, and 4.3 μm rms (30, 80, and 170 microinches rms). Web speeds ranged up to 12.7 m/s (2500 ft/min) and web tensions were 219 N/m (1.25 lbf/in.), 314 N/m (1.79 lbf/in.) and 460 N/m (2.62 lbf/in.).

The measured air film heights were compared with those predicted by the foil bearing equation. Good correlation was achieved for the web moving over the

smoothest surface only. The rougher surfaces did not produce air films that followed theory for the complete speed range. In some cases, the air films followed foil bearing theory at lower speeds but then became nearly constant and independent of speed at higher speeds, significantly below foil bearing predictions. The air films for the highest roughness surface were constant and independent of speed throughout the tested speed range, remaining far below the predictions of foil bearing theory. The reasons for this behavior and the implications for web-roller traction are discussed.

NOMENCLATURE

h = air film thickness between web and cylinder (m)
R = roller radius (m)
T = web tension (N/m)
U_{roller} = roller surface velocity (m/s)
U_{web} = web velocity (m/s)

σ = rms surface roughness (m)
μ = dynamic viscosity of lubricating fluid (Pa-s)

INTRODUCTION

Web quality and efficient web processing are critically dependent upon the thin lubricating air film that exists between moving webs and drive or support rollers. An inadequate film results in increased friction, web abrasion, and resistance to smoothing. An excessive film reduces roller traction, resulting in longitudinal slip and lateral wandering. Foil bearing theory, which has been applied extensively to the problems of magnetic tape recording, can be a very good predictor of air film thickness for smooth surfaces (1-9). Knox and Sweeney (10) are credited with the first application of this theory to web handling problems. Tajuddin (11) also applied the theory to webs and smooth rollers. Predictions for foil bearings with rough surfaces are not available.

Background

In its simplest form, foil bearing theory considers the case of a perfectly flexible two-dimensional non-porous foil, or web, moving over a smooth roller under conditions of incompressible flow. The theory shows that the air film may be divided into three regions 7), as illustrated in Figure 1. Note that the film thickness is greatly exaggerated in the figure's schematic representation of the problem. For example, in this study the largest measured film thicknesses are approximately equal to thickness of the web and correspond to less than 0.03% of the roller radius. Returning to consideration of the three regions in the figure, our principal interest lies in the middle region. This region contains most of the close contact between the web and the roller. The theory predicts that the air film has a constant thickness through this region, and that this thickness is given by the following equation (7).

$$\frac{\mathbf{h}}{\mathbf{R}} = 0.643\left(\frac{6\mu(\mathbf{U}_{\mathbf{web}} + \mathbf{U}_{\mathbf{roller}})}{\mathbf{T}}\right)^{2/3} \qquad \text{Eq. (1)}$$

Note that the velocities of the web and roller are additive, and that different authors provide slightly different values for the leading constant. One may observe that the air film thickness increases with velocity. Consequently, the problem of excessive air films becomes a particular concern as web line speed is increased, as observed by Daly (12). Practical approaches to this problem have centered upon alterations to the roller, notably adding surface texture and machining grooves. However, these attempts to maintain traction by maintaining small air film thickness have been based in empiricism, for it has not been possible to predict the effects of the grooves or the surface roughness upon the air film thickness or the traction.

Consideration of the physical mechanisms through which the traction force between the web and roller is developed provides some insight to the problem. For the case of the web and roller moving at the same velocity, fluid viscosity cannot contribute to the traction force in the constant gap region. With zero streamwise pressure gradient, the fluid velocity profile between the web and roller must be uniform and constant. Thus there is no velocity gradient between the two surfaces and the viscous shear stresses are zero. Pure mechanical friction must provide the traction force. Even for cases in which there is relative motion between the web and roller, the viscous stresses resulting from the velocity gradient between the two surfaces are small and mechanical friction dominates.

This mechanical friction is developed through the contact of the asperities of the roughness of the two surfaces. The amount of contact then must be dependent upon the relationships of the air film thickness between the two surfaces and the statistics of the roughness distributions of the two surfaces. Surface roughness is considered in the tribology literature, with particular emphasis placed upon its effects upon bearing load capacity (13-29). The roughness orientation (lateral, longitudinal or isotropic) is a factor in these changes in load as well as the height distribution. However, the tribology literature does not provide much guidance as to the coupling between the surface roughness and the developed air film thickness. For magnetic tape systems, it has been reported that as the ratio of air film height to rms surface roughness falls below approximately 6, the surface roughness effects on the tape to head separation become important (14, 15). At these heights, asperity contacts become significant and friction was found to result primarily from head-to-tape contact. As one would expect, rougher surfaces lead to high rates of abrasive wear (16, 17).

Objectives

The objectives of the work reported here were to determine the air film thicknesses that developed for a smooth web moving over a stationary cylindrical support for three different cylinder surface finishes with increasing roughness amplitudes. The experimentally measured results were to be compared to the predictions of foil bearing theory.

EXPERIMENTAL APPARATUS AND APPROACH

Web, Cylinder, and Test Loop Apparatus

Air film thickness was determined through optical sensor measurements of the height of a smooth web moving over a stationary cylindrical support surface. The web's wrap angle on the cylinder was approximately 30 degrees, adequate to provide a long constant thickness region. The web was configured in a continuous loop and installed on the apparatus shown in schematic form in Figure 2. Tension is applied to the web loop by a weighted dancer roller wrapped by the web 180 degrees. The grooved drive roller is wrapped more than 180 degrees. Lateral position is controlled by a traversing roller guide point sensor system. More details on the apparatus are provided by Basheer (30) and by King (31). Measurements were performed for web speeds as high as 13.1 m/s (2575 ft/min) and tensions of 219 N/m (1.25 lbf/in.), 314 N/m (1.79 lbf/in.) and 460 N/m (2.62 lbf/in.).

The web was 35.6 μm thick, 152 mm wide polypropylene with a reflective aluminum coating on one side. The web loop was mounted so that the uncoated surface faced the stationary cylinder. The cylinder was aluminum and was finished with three different surface treatments. The surface roughness was measured with an electronic profilometer that provides the root mean square of the surface asperities. The original surface of the cylinder had a measured roughness of 0.76 μm rms. A 75 mm wide full length strip of the cylinder was bead-blasted to a roughness of 4.32 μm rms. A 57.2 mm strip was sandpapered to a roughness of 2.03 μm rms.

Instrumentation

Air film thicknesses were determined from measurements of the position of the top surface of the web performed with an MTI 1000 Fotonic optical sensor. The sensor was positioned to measure the height of the surface at the spanwise center of the cylinder in the middle of the web's wrap, thereby avoiding edge, entrance and exit region effects. The sensor performed its measurements by shining a small spot of infrared light onto the upper, reflective surface of the web and reading the reflected light. Calibration was performed in place by moving the sensor relative to the stationary web with a sliding cam and dial indicator assembly that amplified the motion to provide an accurately measurable displacement at the dial indicator.

The web speed was inferred from the speed of the drive roller as measured with a photodiode reading a rotating pattern attached to the end of the roller. The 180 degree split pattern provided one pulse per roller revolution. Slip between the web and the drive roller thereby was neglected, but great care was taken to monitor system behavior to insure that significant slippage did not occur.

The tension applied to the web was determined directly from the weights suspended from the tensioning apparatus and the geometry of the mechanism.

Data Acquisition and Processing

Measurements were performed through a PC-based data acquisition system. A 286 personal computer hosting a Metrabyte Dash-16F high speed 12 bit data acquisition board acquired and processed the measurements through a BASIC program controlling the board through Labtech Notebook software. The photodiode signal providing drive roller rotational velocity and the Fotonic optical sensor signal corresponding to web height above the cylinder each were acquired at a sampling rate of 2 kHz in two blocks of 5000 samples. Thus the total record length was 5 seconds.

The digitized photodiode signal was processed to count the pulses corresponding to drive roller revolutions with a simple level detection algorithm. Processing of the height signal was complicated by the fact that the web was in the form of a spliced continuous loop. The segments of the height signal corresponding to the passage of the splice beneath the sensor had to be removed from the record to provide a true measure of air film thickness. The splice was much thicker and stiffer than a single layer of web and also had a taped surface with much different optical reflectance. Fortunately, these characteristics made the passage of the splice very easy to recognize. Splice passage segments were detected in the digitized signal and fixed time segments before and after the beginning of the splice were ignored in the signal processing. In this way, false thickness indications of the splice as well as any effects of the splice on the dynamics of the adjacent web were eliminated from the measurement results. The remainder of the height signal was processed to find the mean voltage and the root mean square of the voltage fluctuations. The linearized calibration was used to convert these voltages to mean web height and rms height fluctuation. The air film thickness was assumed to be the difference between this measured mean height and the static calibration zero point taken with the tensioned stationary web resting on the cylinder surface.

The photodiode and Fotonic optical sensor signals were continuously monitored with an oscilloscope and a counter during the course of an experiment to insure that everything was behaving properly. This monitoring process was very important because of the abrasive wear of the aluminum coating on the web. Although this coating did not face the stationary cylinder, it did run against the surface of some rollers during the course of the loop's passage through the apparatus. This contact did result in abrasive wear, particularly at higher web speeds. Due to this problem, it was not possible to perform measurements at the higher velocities for the rougher surfaces. Since the Fotonic sensor calibration was dependent upon the reflectance of the coating, excessive wear caused unacceptable shifts in the calibration. Deterioration of the surface was visible in the oscilloscope trace of the signal as an increase of the level of the fluctuations about the mean. This signal was monitored along with the surface condition to determine when the web loop had to be replaced. This wear also resulted in the accumulation of dust on the stationary cylinder. Care was taken to clean the cylinder surface before each data point was taken to avoid the problem of dust affecting the readings. Attention also was paid to potential problems that could result from static electricity generated by the moving web. No static problems were observed with the aluminum coated web. Later tests with an acrylic coated polypropylene web did exhibit very noticeable levels of static electricity. It is presumed that the aluminum coated web was not susceptible to these problems because it is inherently self-grounding to the conductive aluminum rollers of the test apparatus.

RESULTS AND DISCUSSION

The primary goal of this research was to determine whether different cylinder surface roughnesses produce air film thicknesses that differ from those predicted by foil bearing theory. Accordingly, measurements of mean air film thickness and the root mean square of the thickness fluctuations were performed for the three different surfaces at three different tensions for a range of velocities. The measured mean thicknesses are compared to the predictions of foil bearing theory. First consider the different surfaces individually.

Smooth Surface - 0.76 μm RMS Roughness

The measured and predicted air film thicknesses for the web moving over the original, nominally smooth, cylinder surface are presented in Figure 3. It may be observed that the measurements generally exhibit the same trends as the theory, with thicknesses increasing with web speed and falling with increased tension. However, for the lower speeds and the higher tensions, the measured thicknesses tend to fall somewhat below predictions. Note that these measurements of air film thickness are all relative measurements, taken as the difference between the measured web upper surface position and the zero position measured with the tensioned web stationary on the cylinder. Any errors in this zero position measurement then bias the other measurements, and of course a different zero measurement was performed for each of the different tension cases. Additionally, it was observed that after the web was stopped, it took a finite time for the web to return to the initial zero position. For example, in one case it was found that over the course of approximately 5 minutes, the web height decreased approximately 0.8 μm. This change would be significant in comparing measurements to theory. It is presumed that this decrease corresponded to the escape of air trapped between the stationary web and the cylinder as an effect of the tension applied to the web.

Sanded Surface - 2.03 μm RMS Roughness

The measured and predicted air film thicknesses for the web moving over the sanded cylinder surface are presented in Figure 4. For these cases, it appears that the best agreement with the trends predicted by foil bearing theory occur for lower web speeds. The measured film thicknesses seem to deviate from theoretical trends as the speed increases, with the thicknesses tending to reach a plateau independent of speed and then decrease. The highest tension case does seem to be inconsistent with the other cases, as it exhibits greater thicknesses than the lower tension cases. Again, this inconsistency might be attributed to problems in establishing the zero thickness position. This problem was more severe for the roughened cylinder surfaces. Nevertheless, the highest tension case does appear to follow theoretical trends to higher web speeds than do the lower tension cases.

Bead-Blasted Surface - 4.32 μm RMS Roughness

The measured and predicted air film thicknesses for the roughest surface, the bead-blasted surface, are shown in Figure 5. This figure shows measurements that do not follow the trends of foil bearing theory except at the very lowest velocities and the highest tension. Beyond this low velocity range, the measured air film thicknesses seem to become independent of web speed and much lower than the foil bearing theory predictions. This figure shows that large roughness does cause the developed air film height to be very different from that predicted by foil bearing theory. The lowest tension case never approaches the predictions.

The effects of surface roughness on the air film thickness can be observed more clearly in comparisons of the measurements for the three surfaces at each tension.

Three Surfaces at 219 N/m Tension

The measured air film thicknesses for the lowest tension cases are compared in Figure 6. It may be observed that the smoothest surface case generally follows the predictions of foil bearing theory quite well throughout the tested web speed range. The sanded surface, the medium roughness, measurements follow theory only at the lower speeds and then deviate, staying at a nearly constant thickness as speed increases. The bead-blasted surface, the roughest case, measurements remain very small and independent of web speed throughout the measured speed range. This figure presents a very clear picture of the effects of surface roughness. It suggests that as surface roughness increases, the film thicknesses become independent of web speed and lower than the foil bearing theory predictions. This departure from the behavior predicted by foil bearing theory may occur at some critical velocity.

Three Surfaces at 314 N/m Tension

The measured air film thicknesses for the three surfaces at the medium tension condition are presented in Figure 7. The trends observed in Figure 6 are present but not so dramatically. The increase of tension appears to make the air film thickness behave more like the predictions of foil bearing theory than for the lower tension. Nevertheless, one may observe that at the highest roughness, as web speed increases the measurements fall substantially below predictions and roughly independent of velocity.

Three Surfaces at 460 N/m Tension

The comparison for the cases with the highest tension are shown in Figure 8. The trends exhibited by these measurements are less clear. The measurements tend to follow the foil bearing trends to higher velocities than the lower tension cases, but the relative magnitudes of the three cases appear inconsistent. Again, this inconsistency may, at least in part, be attributed to problems in establishing the initial zero position for the web. This problem is the most severe for the rougher surfaces. Again, the results for the roughest surface tend to deviate from predictions as velocity increases.

Implications for Web-Roller Traction

The meaning of these results can be developed through consideration of a review of some of the relevant characteristics of the traction between a web and roller. First of all, it is believed that good traction depends upon the maintenance of some amount of asperity contact between the web and the roller or cylinder. It is obvious that the amount of asperity contact depends upon both the separation between the web and the roller and the geometry and statistical distribution of the asperities.

The rms of the roughness is not the only statistic of importance. One must consider the radii of curvature of the roughness elements and higher statistical moments of the distribution. Generally, the roughness of a bearing is characterized by relatively large radii of curvature. In other words, the shape of the roughness is more like rolling hills than jagged peaks. The effects of wear on these distributions also must be considered. The burnishing of wear may truncate the largest amplitude asperities, wearing off the peaks.

However, neglecting most of these factors, one can find a crude measure of the beginning of the regime in which good asperity contact and traction occur. This regime is defined by the ratio of the air film thickness to the rms surface roughness. Values of this ratio between 6 and 3 are considered to be the boundaries of the partial lubrication regime of good traction. Accordingly, it then is useful to see how the air film measurements compare to this regime. Figure 9 presents the previous air film thickness measurements divided by the corresponding surface rms roughness.

The results are illuminating when viewed in this form. The figure clearly shows that the cases in which the air film thickness continue to increase with web speed as predicted by foil bearing theory fall in the regime with ratios beyond 3 to 6. In this region, asperity contact is believed to be small. The cases in which the air film thicknesses do not exhibit appreciable increases with velocity correspond to ratios that are generally below 6. In this, what is defined as the partial lubrication regime, asperity contact is believed to become significant.

Asperity contact is neglected in the foil bearing equations, which apply to smooth surfaces. In the constant thickness region of a foil bearing, the equations account for the support of the web through a balance of the pressure difference across the web and the forces resulting from the ratio of the tension on the web to the radius of curvature of the web. Consequently, one might conclude that for the measurement cases in which the film thickness agrees with the predictions of foil bearing theory, the air pressure developed beneath the web provides its primary support. Of course, this support mechanism does not apply if the web is supported completely by the asperities.

For the cases that fall in-between, in the partial lubrication regime, the support of the web is distributed between the air pressure in the film and the mechanical contacts at the peaks of the roughness asperities. Thus, it may be expected that as the asperities begin to provide more and more of the support for the web, the air film thickness will deviate increasingly from the predictions of foil bearing theory. The measurements for the rougher surfaces in this study do exhibit deviations from the predictions of foil bearing theory as the velocity is increased. The question then remains how to predict when the web will ride on the asperities and when it will be supported by the air film. In other words, at what conditions will the air film begin to deviate from the foil bearing predictions?

Note that the roughness does not play an entirely passive role in this process. The tribology literature (13-29) shows that in simple slider bearings, surface roughness can increase or decrease the load capacity of a bearing, depending upon the roughness characteristics. Furthermore, for bearings in which the surfaces both are rough and have relative motion, other factors come in to play. The relative motion of the two surfaces changes the alignment of their roughness asperities with respect the other surface, causing "squeeze-film" effects (14, 15)

The load capacity of a slider bearing is determined by the integral of the pressure distribution developed through the bearing passage. For the foil bearing, a roughness-induced increase in load would increase the pressure between the web and the roller. If there were no asperity contact, the web would be completely supported by this pressure. Then the pressure difference across the web still would be proportional to the web tension divided by the radius of curvature.

If one considers a case with constant tension, the addition of roughness which increases the load would result in a decrease in the radius of curvature. The web would move closer to the roller and contact with asperities. Since the film thickness is an extremely small fraction of the radius of curvature (nominally the roller radius), a very small change in radius of curvature would correspond to a much larger change in the film thickness. Of course, a roughness that produced a decrease in load would result in an increase in film thickness. Thus roughness can alter the air film thickness beneath the web even in cases in which there is no significant asperity contact.

Once there is significant asperity contact and the web is supported primarily by asperity contact, the foil bearing results no longer apply. Some of the measurements results for the roughest surface in this study appear to fall in this regime. For such cases, the air film that develops may be more directly coupled to the characteristics of the roughness.

Thus the result of this study show that the addition of roughness to a stationary support cylinder can decrease the air film thickness between the cylinder and the moving web above it. The film thickness can be reduced to a level at which significant asperity contact occurs. For some cases, as web speed increases, the film thickness can increase following foil bearing theory predictions and then reach a level where it becomes nearly independent of further speed increases. Further study is required to develop accurate means to predict the occurrence of these effects.

CONCLUSIONS

For the conditions of these experiments, the results of the study lead to the following conclusions about the characteristics of the air film between a moving tensioned web and a stationary support cylinder.

1. The air film thickness between the moving web and the smooth stationary cylinder generally follows the predictions of foil bearing theory for the tensions tested. The poorest agreement tends to occur at the lower web speeds.

2. Surface roughness on the stationary cylinder can have a large effect on the air film thickness. For the medium roughness case, good agreement with foil bearing theory occurs for low web speeds and high tension. At higher speeds and lower tensions, the air film thickness deviates from foil bearing theory, becoming independent of web speed.

3. For the roughened cylinder surfaces, the reductions in air film thickness can bring the film down to a level at which significant asperity contact and enhanced traction are expected.

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FIGURES

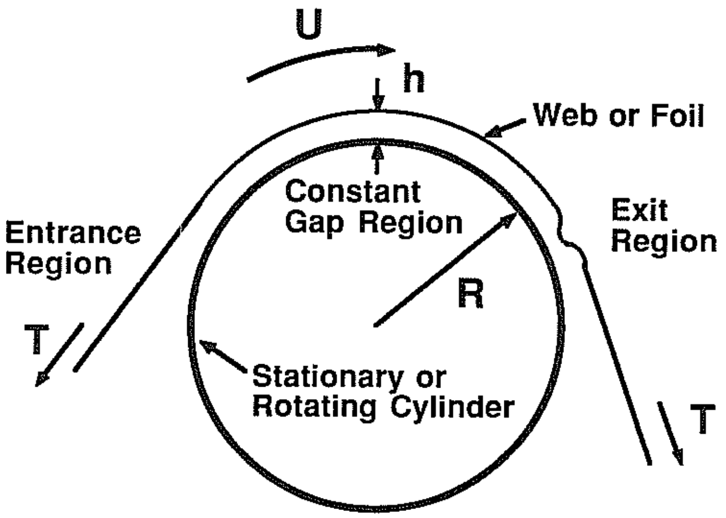

Fig. 1. Schematic of Flexible Foil Bearing

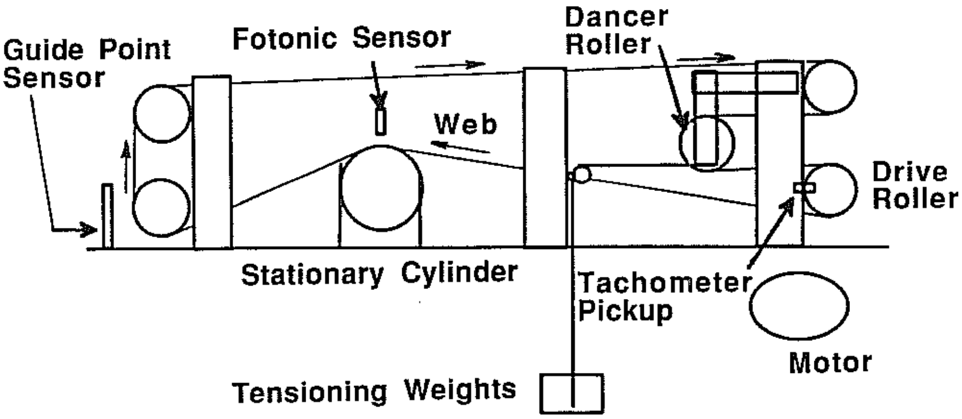

Fig. 2. Schematic of High Speed Continuous Loop Test Apparatus

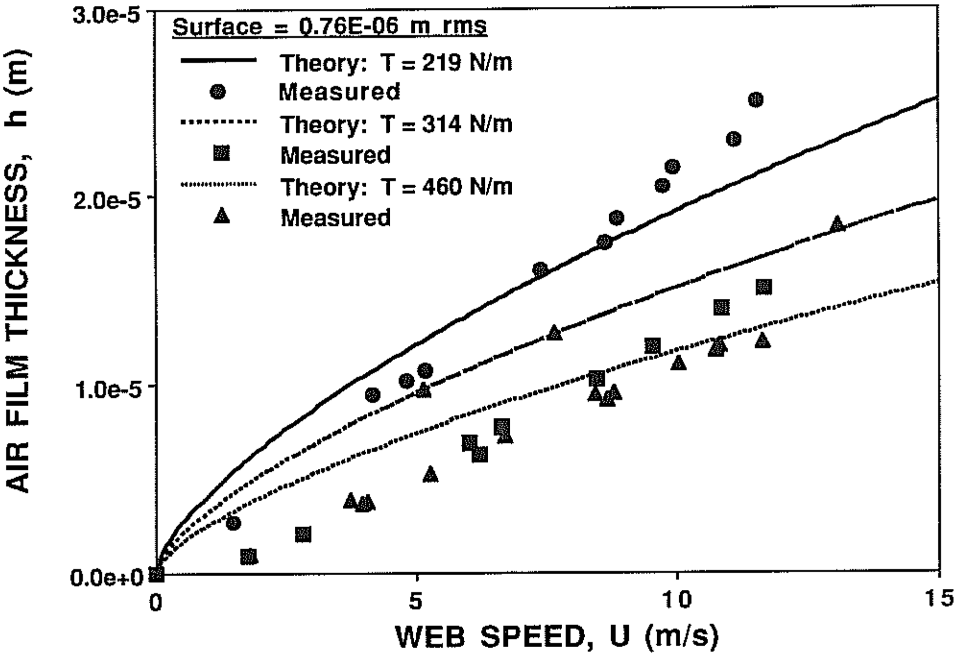

Fig. 3. Air Film Thicknesses for Smooth Surface

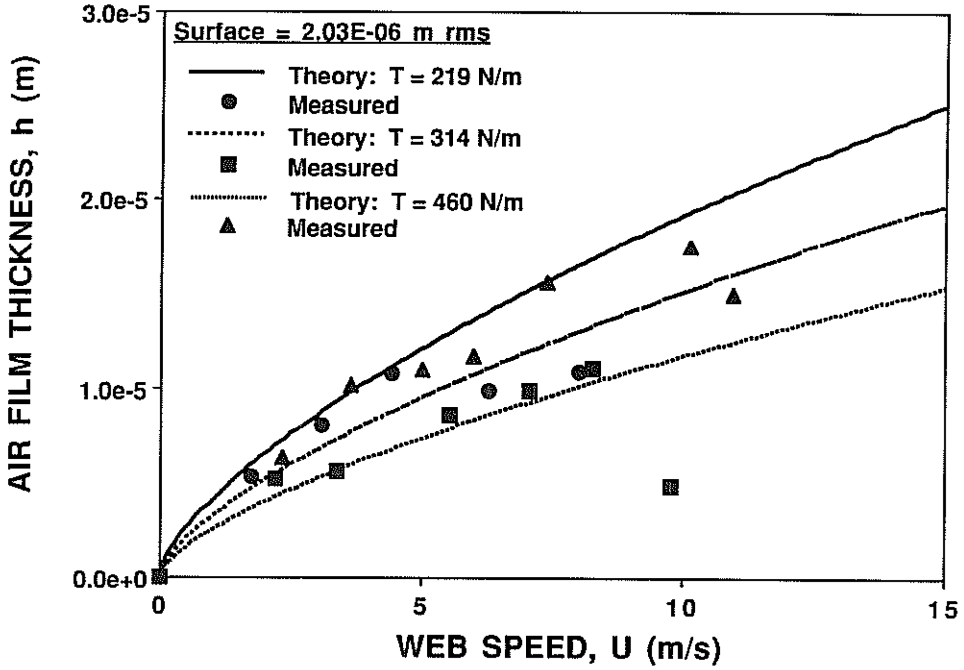

Fig. 4. Air Film Thicknesses for Sanded Surface

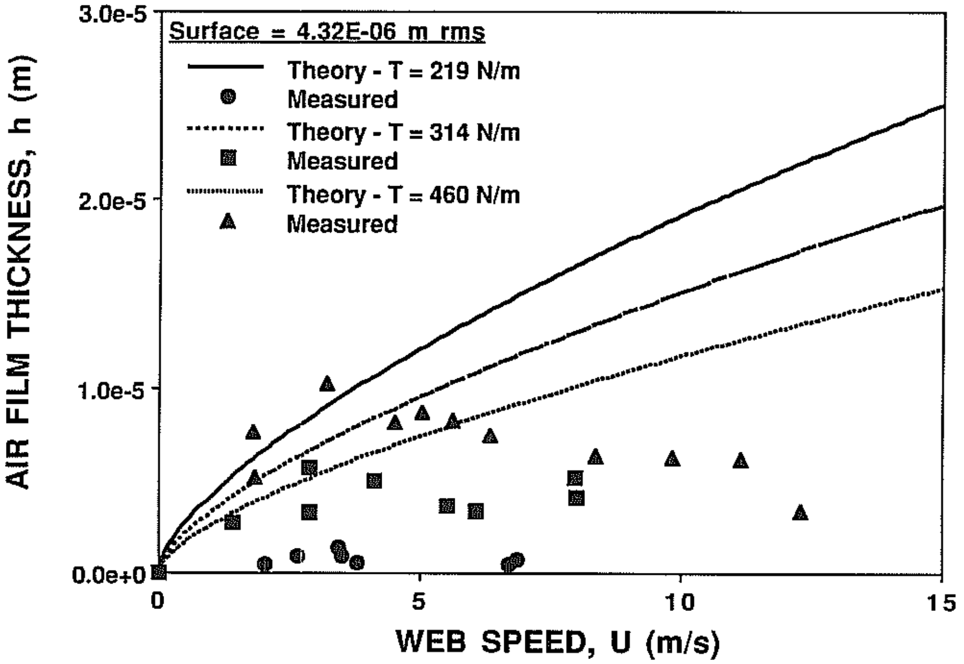

Fig. 5. Air Film Thicknesses for Bead-Blasted Surface

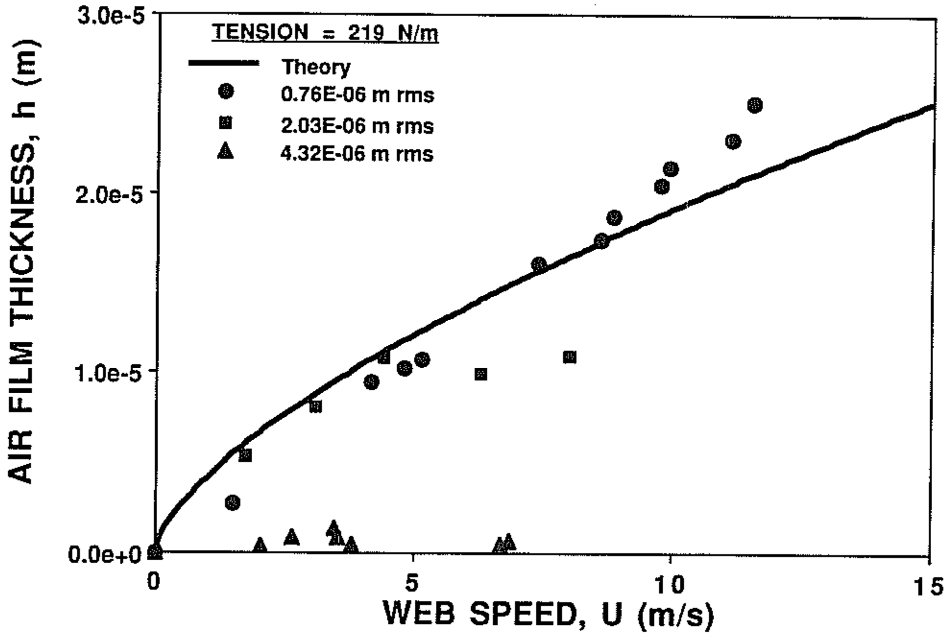

Fig. 6. Surface Dependence of Air Film Thicknesses at Low Tension

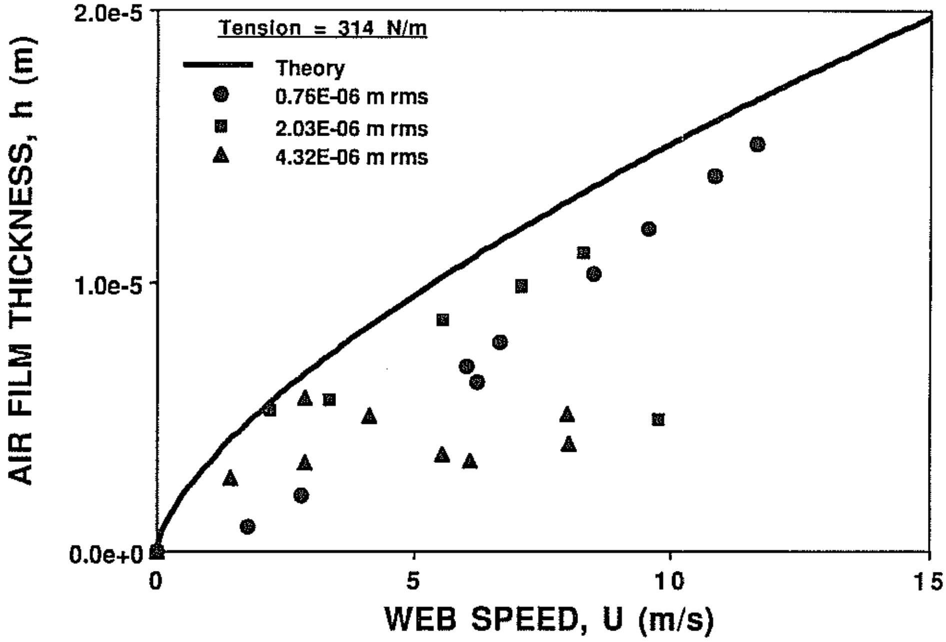

Fig. 7. Surface Dependence of Air Film Thicknesses at Medium Tension

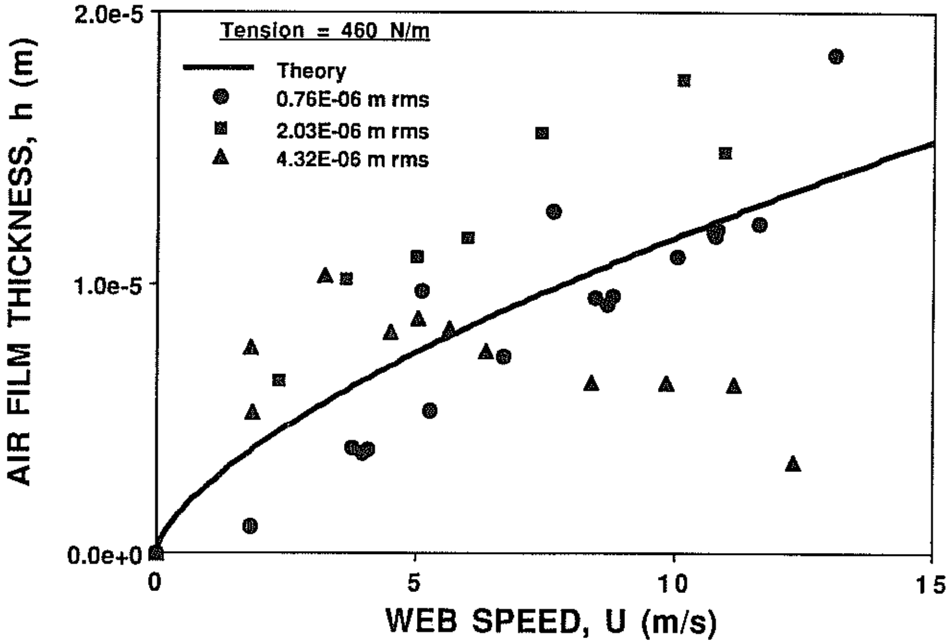

Fig. 8. Surface Dependence of Air Film Thicknesses at High Tension

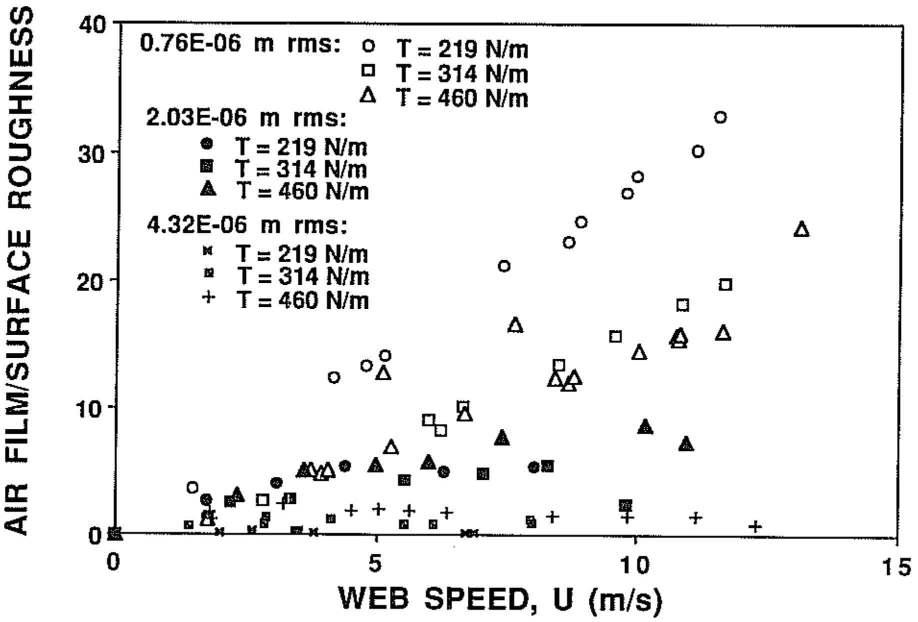

Fig. 9. Air Film Thicknesses Scaled with Surface Roughness

QUESTIONS AND ANSWERS

Q. What is the effect of the shape of the roughness?

A. One of the things that one reads in the tribology literature is that we draw all these pictures of these various spiky roughnesses, but really the wavelength may be fairly large compared to H, but it isn't quite so much like jagged peaks, but more like rolling hills, and if we're assuming a perfectly flexible foil, it may actually be following it fairly well, but it's riding on these very jagged peaks, so we have to look at the probability distribution. How does the roughness wear? Are we truncating the high peaks with wear? Things like that.

Q. How good are the air film thickness measurements? Do they agree with the Knox-Sweeney equation [foil bearing theory]?

A. They're difficult measurements. They're close enough to theory to convince me that they're basically following theory. There have been more careful measurements made that confirm foil bearing theory pretty well, particularly the magnetic tape literature.

Q. How were the measurements of the sensor processed to get the measured "h"?

A. It's an average over many passes of the web.

Q. These measurements were for the case of one surface moving and the other stationary. Have you studied the case with both surfaces moving?

A. No. I think that's very important. I would like to do that, because in the effect of the roughness on the load, the relative motion between the two surfaces is very important. We were running it with the web moving, the roughness stationary. When they're both moving together at the same speed it can be somewhat different. Particularly in the effect of the pressure.

Q. Did you include the effects of the roughness of the surface of the web? Did it have any effects on the measurements?

A. No, we presumed that the web was much smoother than the roller. We did see an effect in doing the calibrations. Shermaine found that the air that was trapped under the web the 0 point [0 film thickness height] calibration escaped from under the stationary web. When the machine was shut off, one could see a very gradual decay of the height of the web as it moved down closer to the cylinder.