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White Light Interferometry of Elastohydrodynamic Lubrication of Foil Bearings

Abstract: This paper describes an experiment performed to verify the one-dimensional model of elastic foil behavior developed by Stahl, White, and Deckert [1]. In the experiment, a loop of tape one-inch wide passes over a stationary recording head, and the air-film thickness between the head and the foil is determined using white light interferometry. Measured data for various experimental conditions are compared with the predictions of the model and also with prior foil-bearing analyses. The influence of parameters such as tape thickness, head radius, tape tension, etc. on the nature of the spacing field is demonstrated.

Introduction

The desire to gain a better understanding of the phenomena associated with tape transport in magnetic recording is frequently cited as one of the main motivating factors in foil-bearing studies of the last two decades. The impact of this important application on the development of foil bearings continues because the technological requirements for recording on flexible media demand that these phenomena be even better understood and controlled. The trend toward higher recording bit densities and higher data transfer rates requires smaller separation between head and tape and larger relative velocity between the two. Moreover, significant and rapid damage to the medium and undue wear of the head must be avoided, hence the importance of maintaining and controlling a suitable air film at the head-to-tape interface.

The interaction between an elastic foil and a fluid film has been extensively studied in recent years. This effort has provided considerable insight into the behavior of foil bearings, but it has not been effectively applied to investigating the performance of noncircular heads and to wave propagation phenomena in tape. In an attempt to analyze such problems, Stahl, White, and Deckert [1] developed a model of the interaction between tape and fluid film that differs in a number of respects from conventional foil bearing studies. In [1] the undeflected straight-line configuration of the tape is used as a reference configuration, whereas in conventional approaches the coordinate system is attached to the surface of the cylindrical head. Conventional foil-bearing analyses employ asymptotic foil boundary conditions; the Stahl, White, and Deckert model, on the other hand, allows one to consider a finite piece of tape and to write appropriate conditions at each end. Finally, the time-dependent terms are an integral part of the formulation in [1], whereas these terms are not usually present in conventional theory because it is mainly concerned with steady-state solutions.

The intent of this paper is to present an experimental study that complements and verifies some aspects of the theory presented in [1]. In particular, we have focused our attention on comparing theory and experiment for the case of the steady-state separation between tape and head. Licht [2] and Ma [3] have provided such a comparison between conventional theory and experimental data. However, because conventional theory is concerned only with asymptotic boundary conditions, those authors did not provide some of the geometrical details which would be required if Stahl et al. were to simulate their experiments. Moreover, most of their tests would constitute a case of large penetration of the head into the tape; a situation for which the linearized theory of [1] is not particularly appropriate. As a consequence, it was decided to design an experiment that closely duplicates the conditions underlying the theoretical considerations in [1].Another feature of the experimental investigations reported in the literature is that the conditions of the experiment lead to rather large separations between the foil and the head, usually greater than three μm. In

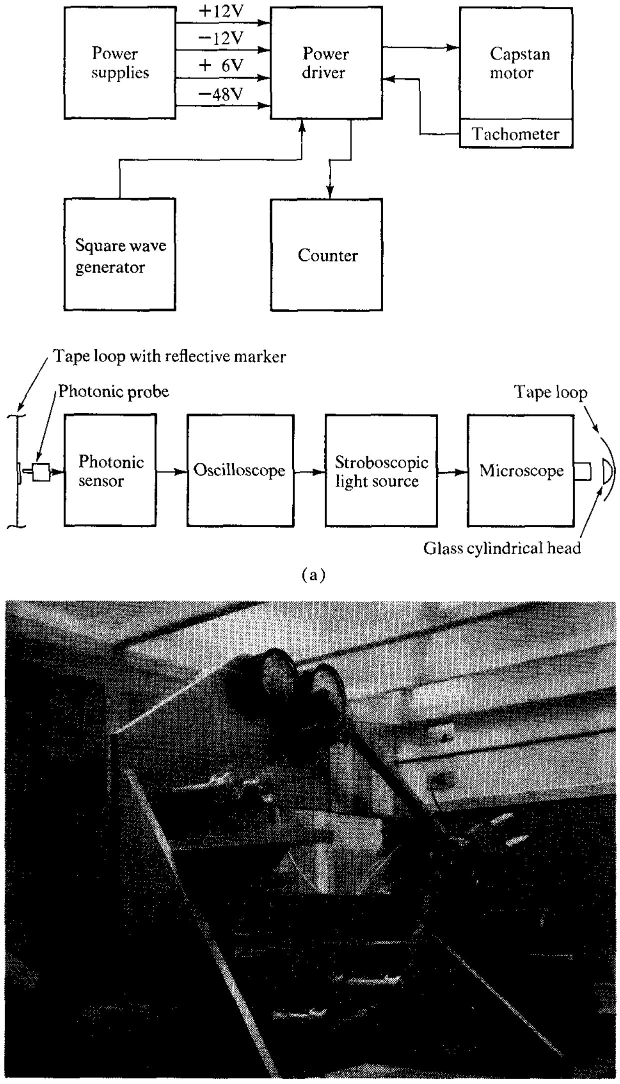


Figure 1 Apparatus for measuring the gap between glass model of the magnetic recording head and the moving tape. (a) Block diagram of system. (b) Photograph of apparatus.

magnetic recording, however, the air film should be one μm or less, as was pointed out in [1]. Only limited data seem to exist for spacings in this region [4]. Hence, another objective of the present work is to provide more data for these low spacings and to compare these data with the model.

To measure these spacings it was decided to explore the use of light interference methods. Some of the early work in this area is that of Lipschutz [5] and Harper, Levenglick, and Wilczynski [6]. These investigators determined the separation of a foil from a cylindrical surface by interpreting the fringe pattern obtained from a specially constructed three-color camera. However, their technique is difficult to use and the interpretation of the photographed fringe patterns is a laborious task. Lin and Sullivan [7] report on a white light interferometric method for measuring thin air films. In contrast to the method presented in [5, 6], this technique uses relatively simple equipment to create and monitor the white light interference pattern. In addition, the resolution for spacings under one μm is excellent and, of course, the interference pattern provides a direct full-field view of the spacing. These features make it an attractive alternative to the commonly used techniques of gap measurement by means such as the capacitance probe [2, 3] or by finding the signal-amplitude loss of a prerecorded signal [4]. In fact, the utility of white light interferometry in measuring sub-μm spacing on flexible media has been demonstrated very recently by Tseng and Talke [9]. The head-medium configuration investigated in their paper, however, is different from the one presented here.

Interferometric technique

The essential elements of the experimental apparatus are shown in Figs. 1 and 2. The test fixture is a parallel-track tape deck using a capstan motor to move the tape, a vacuum column to provide tape tension, a number of air bearings for support and guiding, and a dummy head. The tape deck accomodates a tape loop 0.025 m (1 in.) wide. The tape loop used in the experiments is made of clear Mylar and is approximately 2.44 m in length. A laser goniophotometer used to measure the surface roughness of the Mylar indicates that over 95 percent of the surface area the peak-to-valley distance was under 0.1 μm. The head is a plano-convex cylindrical lens that is considerably wider than the foil. A flexible precision microscale with 127-μm spacing between lines is attached to the lens and is useful in accounting for head curvature when measuring distance along the head from the apex. The microscale is shown in Fig. 3.

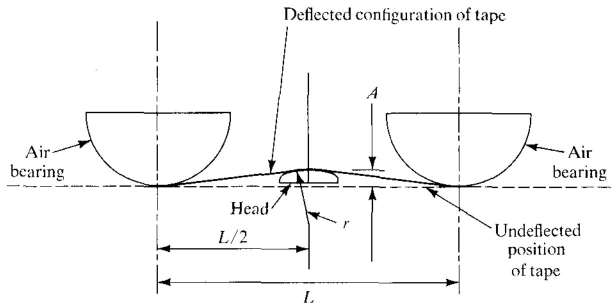
The head assembly and the air bearings on either side of this assembly are mounted on precision slides which permit adjustment of head penetration and the wrap angles over the head [Figs. 2(a) and 2(b)]. The distance between these air bearings is set at 0.084 m. The tape speed is measured by means of an electronic counter and a phototube pickup in conjunction with a 360-line circular digital tachometer disk.

The error in the speed measurement is estimated to be less than 0.5 percent. The tape tension is determined from the dimensions and pressure in the vacuum column. The vacuum is monitored on a Dwyer Magnehelic pressure gauge; the estimated error in the measurement is of the order of one percent. The contribution to the total error in the determination of tension due to inaccuracies involving the measurement of the tape width and the tape loop is negligible.

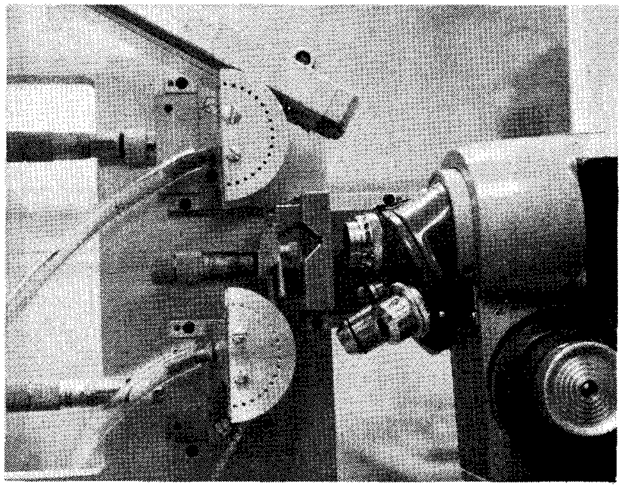
At the heart of the measurement system is an American Optical 3015 T industrial microscope. Using a General Radio 1538-A Strobotac as the microscope illumination source, we can obtain a single flash picture of the interference fringe pattern on 35 mm film. The microscope is mounted to allow viewing the interface through the lens head and was placed on a slide that traverses a direction normal to the stationary frame of the fixture. This feature is important because the field of view of the microscope encompasses only a small portion of the tape. When the microscope is moved from one edge of the tape to the other, the entire spacing at the head-tape interface can be viewed. To ensure that the pictures are not taken when the splice in the tape is in the vicinity of the head, a reflective marker, detected by a photonic sensor, is affixed to the foil to trigger the Strobotac.

Because detailed discussion of the interference phenomena that occur at the head-tape interface and of interpretations of the interference pattern created by a white light source can be found in [7] and in texts such as [8], we confine ourselves to a few brief comments. The color that appears at any point in a thin film depends on the light intensity at those wavelengths that undergo constructive interference. Light at other wavelengths is not visible because of destructive interference. Moreover, because a variation in film thickness leads to a variation in the wavelength intensities that are either strengthened or weakened, the colors that appear depend on film thickness. Newton's color chart shows the colors as a function of the film thickness. An artist's rendition of this chart was published in [7]. Such charts, however, are frequently misleading because they do not exactly match the photographed fringe pattern. This problem can be overcome by constructing a color band chart using the same light source, color correction filters, optics and film as is used in the white light interferometer. The scale shown in Fig. 4 is an example of such a chart. It was made by photographing the fringe pattern produced by placing one optical flat on another in a slightly nonparallel position. Such an arrangement produces a thin wedge-like air film that produces all the colors for various gap widths—from zero to the spacing at which colors become indistinguishable.

The color band chart shown in Fig. 4 covers spacings only up to 1.27 μm. Beyond this spacing the interference pattern degenerates into a sequence of light and dark bands, each pair of light and dark fringes representing an order. Each order spans a spacing of approximately 0.31 μm. We estimate that our measurement for head-to-tape separations less than 1.27 μm is accurate to within ± 0.05 μm, and for distances greater than 1.27 μm the measurement is believed to be correct to within ± 0.15 μm. The principal source of error in these estimates is due to color interpretation. Some error is introduced because of the influence of head curvature on the path length of a light wave, but this contribution is negligible. Since the field of view is about 1.9 mm and the smallest head radius used in the experiments is 12 mm, the maximum error due to curvature is approximately one percent. For the more frequently used larger radius this error is, of course, significantly smaller.



(a)



(b)

Figure 2. Details of the test fixture in Fig. 1. (a) Schematic view of the head and tape region. (b) Closeup of the glass head region of the test fixture.

In some preliminary testing with the apparatus, it proved difficult to obtain stationary fringe patterns because of the large amount of debris that collected at and passed through the head-tape interface. In the initial attempt to alleviate this problem a static eliminator, which prevents the buildup of electrostatic charges, was introduced into the tape path by fastening it between two of the air bearings. This arrangement did not sufficiently alleviate the problem, so that clean air had to be blown across the fixture. The cleaner environment was achieved by placing the apparatus in an enclosure that was open at one end and had a laminar flow bench at the other. The static eliminator was not removed after the fixture was located in front of the flow bench. These modifications to the setup corrected the debris problem.

Test description

The flexibility of the foil-bearing model developed by Stahl et al. permits experimental verification of various aspects of the theory. As mentioned previously, this study focuses on experiments that examine the ability of the model to predict steady-state solutions for cylindrical heads as a limiting case of an initial-value problem.

The correlation of the experimental data with the theoretical results requires the specification of the Young's modulus, E, Poisson's ratio, ν, and the viscosity of air, μ. The parameters μ and ν are assumed to have the constant values 1.81×10^{-5} N-s/m^2 and 0.35, respectively and E was determined to have a value of 4.0×10^9 N/m^2 from tensile tests on an Instron machine. Other parameters that are important to the correlation are the ones varied during the experiments. These parameters were the tape thickness, t, the tape speed, U, the head penetration, A, the tape tension T, and the head radius, r. The following sets of values were used in the experimental program, but not all possible combinations of values of these parameters were utilized: $t = 25.4$, 38.1 and 76.2 μm; $U = 1.27$, 2.54, 3.18 and 5.08 m/s; $A = 0.00127$, 0.00254, 0.00381, 0.00508 and 0.00635 m; $T = 218.91$, 276.70, and 364.26 N/m and $r = 0.02$ and 0.012 m. To ensure that the air-film thickness measurements were valid and reproducible, the case with $t = 38.1$ μm, $A = 0.00381$ m, $U = 2.54$ m/s, and $r = 0.02$ m was repeated four times during the course of the experiments with different loops of tape. In each case the interference photographs were almost identical. Hence we feel that this measurement technique can be made to provide consistent and reproducible results.

To locate the apex of the head, a picture of the static fringe pattern was made, Fig. 3(a). This pattern resulted when the head first made contact with the stationary tape. Knowledge of the location of the apex makes the interpretation of the dynamic fringe patterns relatively straightforward. Figures 3(b) and 3(c) are typical of the kind of dynamic fringe patterns that are obtained. Unfortunately, if we wished to have interference patterns that covered a region from the edge of tape into the uniform interior and from entry to exit, a series of pictures had to be taken. However, because the fringe patterns are remarkably stable it is quite easy to make a composite picture from the individual ones. In fact, Fig. 3(b) was constructed from two pictures, and Fig. 3(c) from four pictures. The color band chart was then used to interpret the photographs.

The fringe pictures that include the precision microscale at the edge of the tape provide, of course, a means of measuring distance across the head. They also facilitate the task of interpreting the fringe patterns, particularly when relatively high spacings occur in the uniform interior region. Because the boundary is always a zone of low spacing, one can always work his way from this area into the higher spacing interior, where the fringe colors tend to be more multivalued. Moreover, we also obtain a field description of this region.

Results and discussion

The results of measurements for two cases and comparisons with the model developed in [1] are shown in Fig. 5. These two cases are typical of the type of results achieved. Figure 5(a) shows the separation between the head and the tape for a small value of penetration, or, equivalently, a small wrap angle. Figure 3(b) is the interference photograph associated with this case. Note that a uniform spacing region has not developed for the choice of parameters of this run. In Fig. 5(b) a uniform spacing zone has formed, and the theoretical profile predicted by the Stahl et al. model for this experiment is more typical of the foil profiles found in the literature. That is, the spacing profile has an entrance zone, a uniform gap region, and an undulatory exit zone. The experimental results, as these graphs show, mirror the analytical ones very well.

Before a quantitative comparison between theory and experiment is attempted, some qualitative observations are in order. First, the shapes of the theoretical profiles [Figs. 5(a) and 5(b)] are very similar to the ones obtained by Licht and Ma in their higher-spacing studies. Moreover, the behavior in the uniform and exit region with variations in tension, speed, penetration, and bending stiffness is also analogous. That is, when the tension is decreased the gap width increases and the amplitude and wavelength of the exit undulation also increase.

Increasing the speed has a comparable effect. We observe, as have others [2, 3], that the film thickness in the central uniform region is essentially independent of the penetration. A similar effect is noted when the stiffness is changed. However, an increase in bending stiffness decreases the length of the constant-gap zone and again increases the amplitude and wavelength of the exit oscillation. One general characteristic of the spacing profile that does differ from earlier reported results [2] is the displacement of the foil when viewed from one edge to the other edge. We find that the spacing profile is very constant from side to side, except in the vicinity of the edge. Here the tape undergoes a sharp drop in spacing in a short distance. For example, in Fig. 3(c) edge effects are present for a distance of about 0.57 mm. Licht observed differences in the spacing profile at greater distances from the edge. However, because his spacings were much larger than those measured in our experiments, side leakage was probably more important in his tests. Licht also noted an antielastic effect at the edge of tape, but we discover no evidence of this effect in our

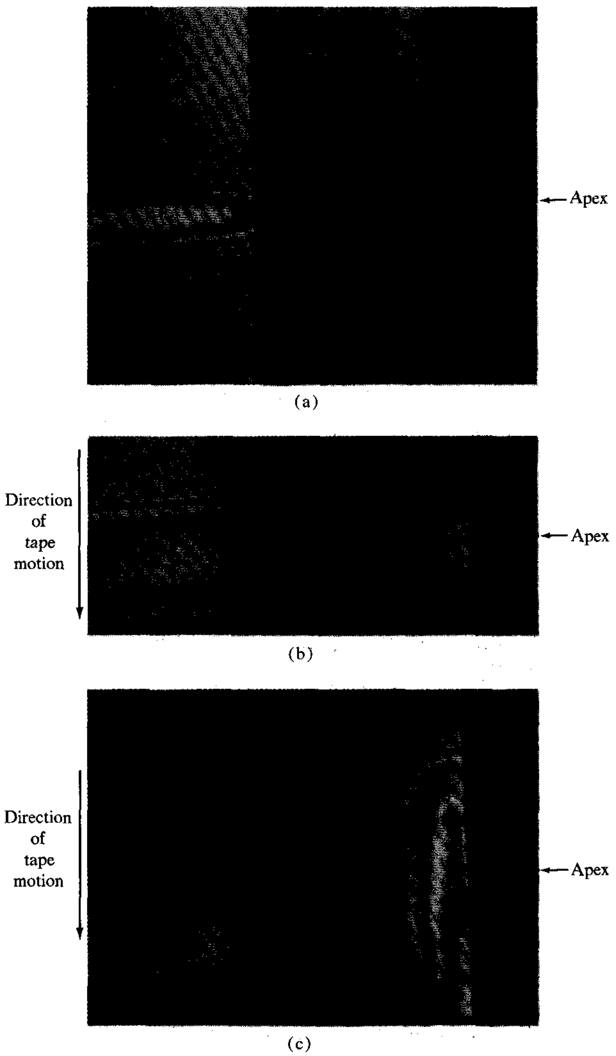


Figure 3 Fringe patterns obtained with the white light interferometric apparatus. (a) Static pattern obtained when the head first makes contact with the tape. (b) Dynamic pattern for head penetration $A = 1.27$ mm. (c) Dynamic pattern for $A = 2.54$ mm. Parameters for (b) and (c): $U = 2.54$ m/s; $T = 276.70$ N/m; and $r = 0.02$ m. (b) and (c) are composite photographs, as explained in the text.

work. The spacing simply continues to decrease in the neighborhood of the edge [see Figs. 3(b) and 3(c)].

The earliest empirical and analytical work on foil bearings appears to be that of Blok and Van Rossum [10]. They found, by assuming that the tape profile consisted of a straight segment followed by a circular arc, that the displacement of the foil from the cylinder in the region of uniformity, h_0, is given by

$$h_0/r = (3\pi\mu U/4\sqrt{2}T)^{2/3} \tag{1}$$

or equivalently,

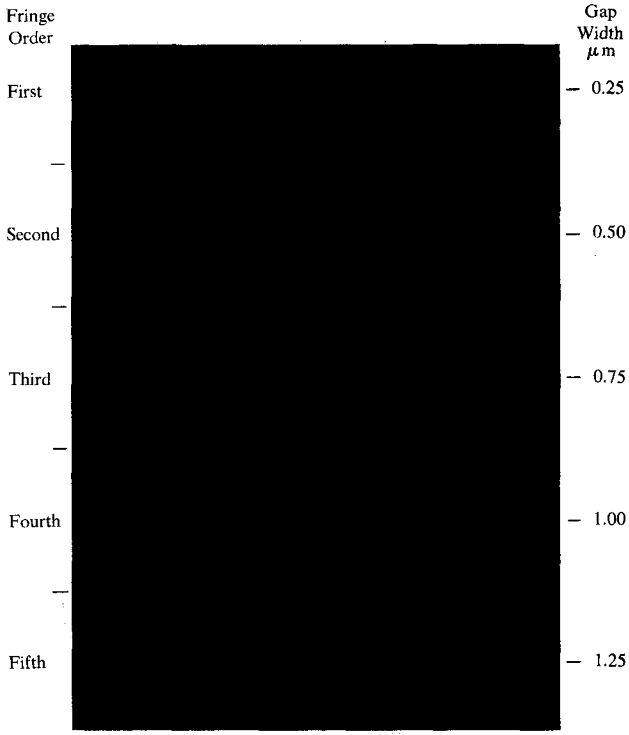


Figure 4 Color band chart for calibration of white light fringes. The photograph is obtained by interferometry of a wedge-shaped gap, providing the full range of calibrating colors.

$$h_0/r\epsilon^{2/3} \fallingdotseq 0.426; \tag{2}$$

here

$$\epsilon = 6\mu U/T, \tag{3}$$

the foil bearing number. Koh and Langlois [11] rederived Eq. (1) a number of years later. Both of these studies assumed the foil to be perfectly flexible and the air film to be incompressible. These same assumptions were used by Eshel and Elrod [12] in their more rigorous derivation of the differential equation and boundary conditions governing the behavior of a perfectly flexible foil. By numerically integrating their equation, they found that

$$h_0/r\epsilon^{2/3} = 0.643, \tag{4}$$

and (4) is the generally accepted result. In [13] they extended their analysis to include the influence of stiffness on the characteristics of foil bearings of infinite width. They found that the right side of Eq. (4) decreases slightly for values of the bending parameter,

$$\sigma = D/Tr^2\epsilon^{2/3}, \tag{5}$$

between 0 and 1.5. In (5) D denotes the flexural rigidity of the tape, i.e.,

$$D = Et^3/12(1-\nu^2). \tag{6}$$

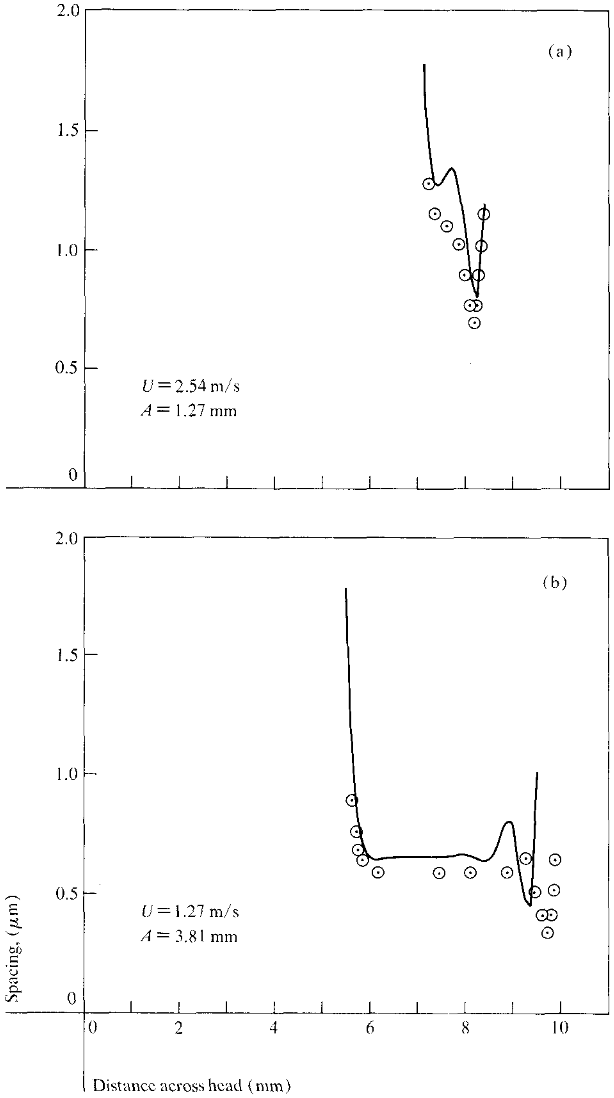


Figure 5 Comparison of experimentally measured (points) and theoretical (continuous line) values of the separation between head and tape. Parameters: $T = 276.70$ N/m; $t = 38.1$ m; and $r = 0.02$ m. (a) Separation for a small value of head penetration. (b) Separation for the case of a uniform spacing zone.

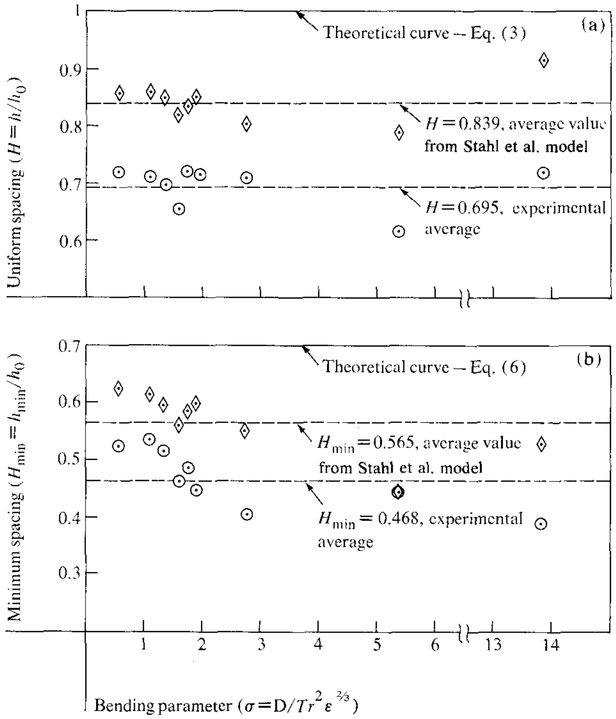


Figure 6 Comparison of experimental and theoretical values for separation between head and tape vs the bending parameter, σ. The line is the result from Eq. (4); the diamonds from the model of Stahl et al. and the circles are experimental. (a) Spacing in the uniform-gap region. (b) Minimum separation, normalized with respect to the theoretical value of Eq. (4).

Eshel and Elrod also determined the value of the minimum spacing, $h_{\min}$, and found for the perfectly flexible foil the ratio

$$H_{\min} = h_{\min}/h_0 = 0.718. \qquad (7)$$

With stiffness included in the analysis, it was discovered that $H_{\min}$ decreases very slowly when $0 < \sigma < 1$. Eshel and Elrod also determined the relationship between amplitude and angular extent of the undulation in the exit region and the bending parameter.

In Fig. 6(a), a comparison is made between the experimental and predicted values from the model of Stahl et al. and Eq. (4) of the spacing in the uniform gap region. This graph shows that the values predicted by the model constantly exceed those obtained in the experiments and that both of these results are less than the spacings predicted by (4). In fact, the ratio between the predicted gap width in the uniform region from the model of Stahl et al. and from (4) varies between 0.787 and 0.912, giving an average value of 0.839 and an average deviation of 30.5 percent from the theoretical values of (4) and an average deviation of 17.2 percent from the predictions of the model of Stahl et al. In comparison, Licht found that his average deviation was only 5.4 percent from the theoretical value of (4). Most of Ma's data on the other hand seemed to fit Eq. (1) best and so there was about 33.7 percent average deviation between his results and the predictions of (4). This discrepancy between these findings and Licht and Ma is somewhat surprising, because most of their experiments produced uniform spacings in the same range of values. It is difficult to identify the possible reason for these differences because Ma does not indicate the tape thickness and tape width he used. However, Ma's tape had a relatively high value of surface roughness which could have reduced his spacings, and possibly side leakage and bending stiffness were more pronounced in his experiments than in Licht's study.

Licht achieved very good agreement between his experimental results and the theory developed in [12, 13]. However, the predictions of this theory for the parameters of this study do not coincide well with the model of Stahl et al., or our experimental results. In an attempt to explain this lack of agreement we returned to the case shown in Fig. 5(b) and recalculated the spacing distribution, removing bending stiffness and slip-flow effects from the model; the compressibility of the air film, however, was retained. This calculation produced a uniform spacing of 0.8 μm, which is very close to the 0.0825 μm predicted by (4). Next, bending was returned to the model, but slip flow was omitted. Now the uniform spacing was in the neighborhood of 0.737 μm. These calculations seem to indicate that, for spacings in the vicinity of one μm, bending stiffness and slip flow have a more important effect than they do at higher spacing.

We also found that the experimental values of displacement were consistently lower than the corresponding numerical data from the model of Stahl et al. This characteristic undoubtedly reflects the differences between assumed and actual elastic properties of the tape and side leakage. In regard to the latter, we find that a greater difference between the results occurred at higher spacings than at lower ones, and we feel that this phenomenon occurred because better seals were achieved at the edges in the low spacing case. A difference between the boundary conditions assumed in the model (simply supported) and the actual conditions over the air bearings could also account for some of the discrepancy.

One further observation about Fig. 6(a), (and also about the data in subsequent figures): the theoretical points from the model of Stahl et al. exhibit a scatter which is characteristic of experimental data. This characteristic is somewhat unusual but may be due to the fact that slip-flow effects have been incorporated into the model.

The minimum displacement, normalized with respect to the theoretical value of (4), is shown in Fig. 6(b). The characteristics of this graph are similar to those of Fig. 6(a). Both the average value for the model of Stahl et al., 0.565, and for the experimental data, 0.468, are less than the value predicted by Eq. (7). These values represent average deviations of 21.3 percent and 34.8 percent, respectively, from the theoretical results of (7). Licht again achieved much closer agreement with this result. His average deviation was of the order of four percent. The reasons mentioned above to account for the differences in the earlier results are also probably responsible for the differences encountered here.

Figures 7(a) and 7(b) present a comparison between theory and experiment for the peak-to-trough amplitude

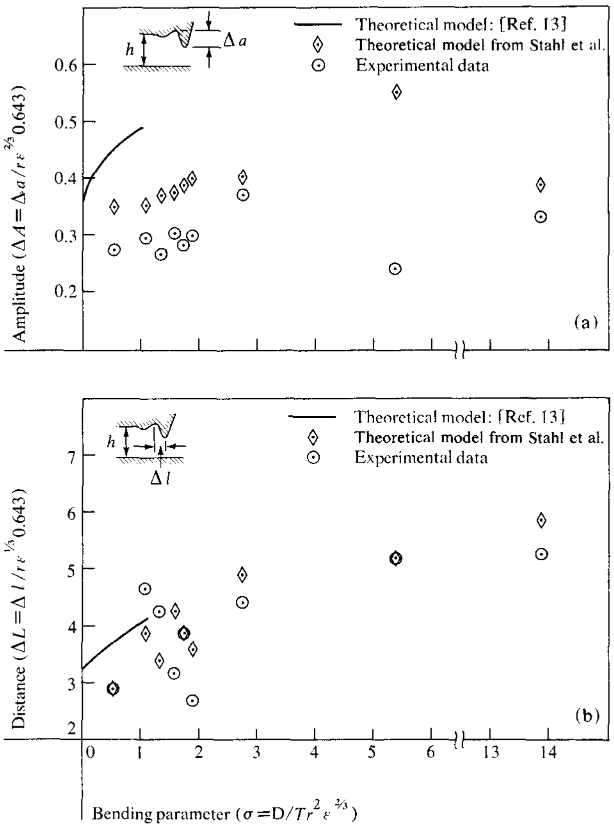


Figure 7 Comparison of experimental and theoretical data for undulation in the exit zone. The line segments are theoretical values from Ref. [13]; the diamonds are theoretical values from the model of Stahl et al.; and the circles are experimental values. (a) Peak-to-trough-amplitude of the last undulation in the exit region. (b) Corresponding distance subtended by the last extremum points.

of the last undulation in the exit region, Δa, and the corresponding distance subtended by the last extremum points, Δl, respectively. The results are presented in dimensionless form vs the bending parameter. The theoretical curves shown in these graphs are based on data presented in Ref. [13]. Once again the measured peak-to-trough amplitudes were lower than both theoretical predictions. This trend is not apparent in the graph of Fig. 7(b), however. Here some of the experimental data are greater in value than the theoretical ones. The last two graphs show that the amplitude and wavelength of the exit undulation tend to increase with increasing values of the bending parameter.

The observations of the preceding paragraph concerning Δa must be tempered because the potential error in the spacing measurement is a significant percentage of this spacing difference; hence the stated conclusions might have limitations of accuracy.

Conclusions

We have shown that the steady-state predictions of the model described in [1] are in substantial agreement with the experiments presented here. Moreover, this agreement was achieved for spacings that are appropriate for magnetic recording, i.e., for spacings in the neighborhood of one μm and less. Hence it seems that the theory may be accurate and flexible enough to investigate a variety of problems in this low-spacing domain. In particular, it appears well suited to exploring the effect of complex head configurations on the head-to-tape separation.

We have also demonstrated that white light interferometry is an effective way to experimentally investigate a class of foil-bearing problems for the cases of very thin films. The simplicity of the equipment and the excellent resolution over the full field of view make it an accurate and attractive technique.

Acknowledgments

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