Preferred citation: D. Atack and D.R. Axelrad. Comments on holographic interferometry. In **The Fundamental Properties of Paper Related to its Uses**, *Trans. of the Vth Fund. Res. Symp. Cambridge, 1973*, (F. Bolam, ed.), pp 101–103, FRC, Manchester, 2018. DOI: 10.15376/frc.1973.1.101.

COMMENTS ON HOLOGRAPHIC INTERFEROMETRY

D. ATACK, Applied Physics Division, Pulp & Paper Research Institute of Canada, Montreal and D. R. AXELRAD, Department of Mechanical Engineering, McGill University, Montreal, Canada

---

CONCERNING Lyne & Hazell's paper, *Formation testing as a means of monitoring strength uniformity*, particularly with reference to the use of holographic interferometry, we wish to make the following comments—

1. In this paper, the remark 'the fringes which represent lines of equal displacement. . . .' (page 84) and the same remark repeated on page 92 with reference to a so-called 'coefficient of variation of the strain. . . .' is erroneous.

Fringes representing 'lines of equal displacement' occur in holographic interferometry only in the case of vibrating membranes as demonstrated by Prof. Hazell himself—see references.[1, 2] To the best of our knowledge, the statements above do not hold in any other case of holographic interferometry.

2. Again the statement on page 84 concerning 'samples 1, 2, 4, 7 and 10 were submitted to strain analysis, since the fringes that formed on their holographic reconstructions were free of out-of-plane effects' as well as a similar statement on page 92 and the explanation given in the appendix are untrue.

Contrary to the work of other researches up to date, as well as our own experimental experience, out-of-plane motion is always present in tensile testing of paper. This experience is in fact in contrast to Lyne & Hazell's contention.

According to the well-known concepts of holographic interferometry, if observed fringes move, an essentially in-plane motion has occurred and, if the fringes remain stationary, an out-of-plane motion has occurred. Following, for example, the basic text of Collier *et al.*,[3] the phase

Under the chairmanship of Dr H. Corte

difference between two reflecting light wave vectors from the object in terms of the wavelength λ of the used light source and the displacement vector Δr of a surface point can be expressed by—

$$\delta = \left(\frac{2\pi}{\lambda}\right) \Delta r \cdot (n_{s1} - n_{s2}) \qquad \text{(Equation } \mathit{15.8}\text{, Collier, page 436)}$$

It is obvious that, if the difference vector $(n_{s1}-n_{s2})$ is in the same direction as Δr, we have in-plane motion of the observed point; if $(n_{s1}-n_{s2})$ is perpendicular to Δr, an out-of-plane motion will occur. This is also evident from the diagram below—

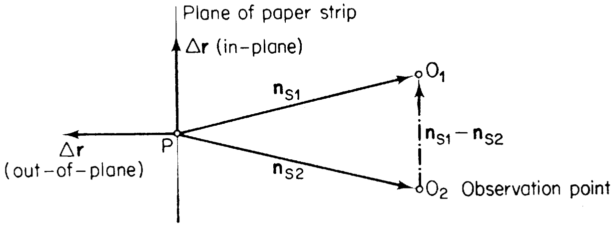

Fig. 1

The right side of this relationship (equation *15.8*) is equal to zero only for an out-of-plane motion or when the *observed fringes do not move* and has its maximum value for an *in-plane motion or when the fringes move*.

Since Lyne & Hazell's observations indicate no observation of fringe movement, only out-of-plane motion occurred in their experiments.

3. Although several other comments can be made on the experimental set-up and probable sources of errors in the testing procedure (on the basis of their own experimental work), out-of-plane motion is always present in stress holographic interferometry of paper. This out-of-plane motion is associated with the observed rheological properties of paper. Again, Lyne & Hazell do not consider stress relaxation of the paper strip investigated by them. Furthermore, the presentation discussing the strain variation in the sheet in comparison with formation testing is unfortunate, since direct strain measurements by the use of holographic interferometry cannot be made. In order to obtain directly strain measures, a technique discussed by Saito *et al.*(4) must be employed, which is somewhat similar to the well-known moiré fringe technique. For this reason, the present authors employ an experimental method(5, 6) that aims at determining the occurring 'micro-deformation' and their corresponding distributions along scanning lines of the material sample. More recently, this method has been applied to the investigation of kraft and newsprint paper subjected to a plane stress situation and including the creep behaviour of the paper samples during the testing.[7]

References

1. Powell, R. L. and Stetson, K. A., *J. Opt. Soc. Amer.*, 1965, **55**, 1 593
2. Olson, M. D. and Hazell, C. R., *Real time vibration analysis of rib-stiffened plates by holographic interferometry*, International Symposium on Experimental Mechanics (University of Waterloo, Ontario, Canada, 1972)
3. Collier, R. S. *et al.*, *Optical Holography* (Academic Press, New York, 1971)
4. Saito, H., Yamaguchi, I. and Nakajima, T., *Application of holographic interferometry to mechanical experiments*, Proc. U.S.–Japan Seminar on Processing by Holography, Washington, D.C., 1969 (Plenum Press, New York, 1971)
5. Axelrad, D. R. and Kalousek, J., *Stress holographic interferometry*, Micromechanics of Solids Lab., Reprint 71–7 (McGill University, Montreal, 1972)
6. Kalousek, J., *Experimental investigation of the deformation of structured media* (Ph.D. Thesis, McGill University, Montreal, 1973, unpublished)
7. Axelrad, D. R., Kalousek, J. and Broadway, A., *Experimental investigation on the mechanical strength of paper*, Micromechanics of Solids Lab., Reprint 73–2 (McGill University, Montreal, 1973)

Transcription of Discussion

Discussion

Mr D. Attwood It is quite true, Prof. Wahren, that a more comprehensive description of variations in the standard deviation is provided by the use of power spectra, but insufficient to use any mathematics based on scientific analysis. There is danger in a one-dimensional approach.

Prof. D. Wahren The kind of analysis that we have used required that one has a statistical process with approximately normal distribution on a sheet that is the result of such a process. Your instance applies to wire mark, for example, where a periodic function is superimposed on the process. To measure wire mark, we also use a line to scan the sample. We tilt the scanning line and, when it is parallel with the wire mark in the web, we get an intense periodic signal, which is a good indication of the degree of wire mark. It is further stated in our paper that anisotropic random sheets possess different spectra in different directions (see Fig. 9). Fig. 41 shows good correlation between the measured spectra of an anisotropic non-woven sample and the corresponding anisotropic random sheet.

Dr C. T. J. Dodson My observation relates to Mr Radvan's comment: you remember that he said you could detect the departure from randomness by counting the number of fibres intersecting with scan lines and Prof. Wahren replied that this gives you the integral of a curve. In fact, you can get the whole curve if you use different lengths of scan line.

Firstly, Dr Lyne, could you comment on the significance of the thirty fringes that occur in the observed regions and, secondly, can you make a guess—and I am sure you have thought about it long and hard—about the intervals of length on samples that correspond to your fringe intervals?

Dr M. B. Lyne There are 25–30 fringes on the paper samples shown in Fig. 2 and 3 and the sample is approximately 9 cm long, so the fringes were separated by about 3 mm. As mentioned in the addendum, the fringes represent, to a reasonable approximation, half λ displacements along the bisector of

Under the chairmanship of Dr H. Corte

the viewing and illuminating paths. Therefore, for simple motions, you could count the number of fringes between two points on the paper surface and multiply by half λ to get the displacement for the component along the bisector.

Dr D. Atack I was interested in seeing some of your holograms Dr Lyne taken more recently in Stockholm, but not reproduced in your paper. It is apparent that there is much more speckling on the holograms taken in the Swedish laboratory, which I suspect is due to a large in-plane component. The holograms presented in the paper contain, we believe, no in-plane component.

Dr Lyne Pictures of holograms can be made of a real or a conjugate virtual image. The microscopic study holograms were photographed by projecting the real image directly on to photographic film, whereas all the other holograms were photographed as virtual images. The magnification and means of projection in the microscopic study were the cause of greater speckle in those illustrations.

Dr K. Ebeling I would like to ask if you have considered the role of the liquid crystal coating on the temperature profile results. It seems to me that the coating can either share part of the load (that is, be under tension) or it can be passive during the straining experiment.

If the coating layer is under tension, then it will undergo thermal phenomena related to the Kelvin's thermoelastic effect. Depending on the nature of deformation (elastic or plastic), the sign of the heat phenomena can be positive or negative. The point I wanted to make is that, in such a case, the thermal phenomena of the coating will be superimposed on the thermal phenomena of the paper.

If the coating layer would be totally passive during the straining, the dynamic nature of the heat transfer is affected by the coating layer. During the elastic region of straining, paper tends to cool—that is, to absorb heat. This means that the heat generation associated with the apparent plastic deformation has to go on for some time before the heat absorption will be balanced out. Usually, this takes place at about 1 per cent elongation. Only after this elongation will the continuation of plastic straining generate heat in the specimen.

Dr Lyne The liquid crystal compound was a grease-like substance and had no discernable effect on the tensile strength. As mentioned in the paper, the thermal measurements (allowing a crude correction for the coating on the basis of relative weights of paper and coating) gave values that agreed closely with large area infra-red scan study. The temperature drop during initial elastic strain is negligible as measured by both techniques. I think a more definitive experiment, however, might be made using an infra-red microscope that is now commercially available.

Prof. L. Göttsching On the holographic method described, it surely needs more skill and effort compared with the moiré technique to evaluate the strain distribution of the paper assembled under stress, knowing that the application of this technique requires, for example, the printing of the paper investigated, which means a certain manipulation. What are the advantages of the holographic techniques in this special field of research?

Dr Lyne As mentioned in the paper, we tried moiré techniques first. We printed the finest grid possible on newsprint and used a suitable analyser plate over the top. We found that the technique had insufficient sensitivity to generate any useful information about the coefficient of variation of strain of the paper. The main advantage of the holographic method is that there is no interference whatsoever with the straining of the paper; it is a completely external sensing technique. It has very great sensitivity—down to the range of half λ displacements. That is certainly much greater than one could anticipate from the moiré techniques described in the text.

Dr J. A. Van den Akker Is it fair to say that, in holographic interferometry, we are dealing with a moiré effect in the diffraction pattern on the plate?

Dr Lyne There is a close analogy between moiré and holographic interferometry. I would direct your attention to two papers by my colleague Dr Nils Abramson of the Royal Institute of Technology in Stockholm [*Nature Physical Science*, 1971, **231** (20)] and reference 14 in the addendum.

The Chairman I would like to comment myself at this point. I understand Dr Lyne, that your coefficient of variation of the distribution of the local displacement is based on forty numbers and that the displacements refer to pairs of points that were originally separated by something like 3 or 4 mm, this order of magnitude. This would be the dimension of the areas of inspection, the small areas we are looking at. If one compares the local non-uniform extension of the sample with the mass that is present in the locality, then ideally one would like to compare areas of exactly the same size. The areas on which your coefficients of variations for the formation numbers are based are quite different and this rules out a direct comparison. The reason for making this point is this: Dr Dodson, in the paper he gives tomorrow, derived a very simple formula that relates the coefficient of variation for the extension (d) to the coefficient of variation for the grammage in the same areas (b)—

$$d = b/(1+b^2)$$

If b is 7 or 8 per cent, the square is small compared with unity and one would expect a linear relationship between the two coefficients of variation, as shown in your illustration. If the areas on which the coefficients of variation for the grammage are based are much smaller, however, the denominator will vary, because the variance of the grammage is (roughly speaking) inversely proportional to the area of inspection. One would not then expect a straight-line relationship between d and b of the type shown in your graph. This surprised me and I wonder if you have any comments to make.

Dr Lyne As I mentioned in the paper, we are dealing with a macroscopic fringe separation. Certainly, the formation inspection area is much smaller. I think it is an inherent problem in analysing fringe patterns that there will always be a macroscopic distance between the fringes. As the increment of strain between exposures of the hologram plate increases, the fringe order increases, but the fringe contrast decreases. In other words, there is a cross-over here of wanting a sufficient number of fringes to give some reasonable information about coefficient of variation, but not wanting so many fringes that they cannot be resolved.

Dr J. Mardon I would like to take issue with Prof. Wahren on his comments on two-wire forming at the end of his presentation. This is far too important a subject to be left with a misapprehension in the minds of the audience. It is not correct to deal with two-wire formers as one generic type. The four kinds of two-wire formers form three very clearly distinguishable types. Only one of these will produce paper better formed than on a properly operated flat wire machine. This one type is highly susceptible to wire mark. The other two types (which include three commercial designs) produce paper that is more badly formed than the common flat wire paper properly made, which will in fact print just as well.

Dr J. Grant I am reluctant to enter too deeply into the controversy between Prof. Wahren and Dr Mardon on the relative merits of two-wire newsprint machines, but I would refer to some rigidly controlled trials in which newsprint was run at high speed on Fourdrinier machines and on two entirely different two-wire machines. Apart from the shadowmarking, which Dr Mardon has already mentioned, there was really little difference in the essential physical properties of the papers made by the three different methods. There was, however, one outstanding difference, which I think is quite relevant and that was in the distribution of the loading between the two sides of the paper. With the Fourdrinier-made paper, there was a very marked difference between the two sides, giving rise to a pronounced two-sidedness; with both the two-wire machines, there was almost uniform distribution throughout the cross-section of the sheet as shown by splitting into four layers and analysing. I think this is quite an important matter when we are considering the structure of the sheet in relation to its properties.

Dr Mardon I have spent five years and a great proportion of my time thinking about this, because decisions of millions of dollars hang on it. Although Dr Grant is correct in his general statement, each of the two-wire former types have a completely different form of fibre distribution and a completely different form of fibre distribution if used on loaded sheets, so much so that, if we take a sheet of unknown origin and examine it simply by splitting it and looking at the drainage characteristics of the different layers, we can tell without any difficulty at all on which type of machine it has been made.

The Chairman You can make good and bad paper on any machine, I mean uniform or non-uniform paper.

Dr Dodson Whereas the fringes are not attached to real points in the paper, is it possible to make an analysis across the fringe pattern?

Dr Lyne I imagine this would be possible, although I have not done so.

Prof. D. R. Axelrad The slides to our contribution explain a lot, particularly in relation to this last question. An analysis across the fringe pattern can certainly be made. If you understand the fringe pattern in the proper manner and you know the interpretation required for this fringe pattern, it becomes very obvious when out-of-plane or in-plane motion has occurred. Normally, the out-of-plane motion is not difficult to observe, but rather difficult to measure.

Dr Lyne To the contribution by Dr Atack and Prof. Axelrad, I would like to comment briefly, especially that the addendum to the paper by Prof. Hazell and myself was intended to provide extra information about our experimental techniques and means of analysis, thus (I believe) it has answered most of the points raised in the contribution.

As my co-author, Prof. Hazell, is at present on sabbatical leave and could not attend the symposium, he has written to request that the following comment be made in response to point (*i*) of the contribution by Dr Atack and Prof. Axelrad—

> I have never suggested that 'lines of equal displacement occur in holographic interferometry only in the case of vibrating membranes', nor did I demonstrate this in their reference.[2] Fringes do represent lines of equal displacement, for example, in the case of rigid body rotation.

To the question of the contribution of possible out-of-place components, I would say that local components are probably present, because paper is a heterogeneous material, but I doubt the presence of macro-wrinkles.

There is a danger that the fringes in Fig. 2 & 3 will be interpreted as surface contour lines. A simple demonstration can be made to show that they are *not* contour lines. We altered the magnitude of the increment of strain applied between exposures of the holographic plate. If longitudinal wrinkles were present in the paper sample, their size would not change due to an alteration in the final strain increment (the webs were already prestrained to 90 per cent of their rupture extention). When the final strain increment was lessened, however, the deviations of each fringe from a straight line became progressively more coarse. This is expected by classical interferometry theory, but cannot be explained by longitudinal wrinkling.

Finally, to apply a perspective to this work, the first holographic interferometry was done in 1965 and we did more of these experiments in 1971. Analytical techniques are mushrooming in this field and it is to be expected that more sophisticated techniques such as the more recent multiple viewing angle approaches will be used in the future to separate and measure local in-plane and out-of-plane components.

I would like to thank Dr Bill Nixon of the Engineering Department at Cambridge for making possible the display of our interference holograms.

Mr B. Radvan I would like to ask Dr Lyne to speculate a little. He has quite properly disregarded boundary areas, but in many ways they may be interesting too. Your slides showed fringes near to the jaws: they are very straight, then become more and more curved, as one would intuitively expect; but it is not as simple as that. Obviously, we are dealing with a phenomenon of stress gradients spreading out. This could be a very important property in papermaking. In transmitting type impression, for instance, one does not want stress gradients to spread. I attempted to measure the distances between the fringes on your photographs without any special result, but I wonder if there are any results on long-fibred papers. Do you plan to do any?

Dr Lyne Boundary layers are quite interesting, of course, but their analysis is always more complex. We have looked at kraft softwood pulps in the edge tear configuration and in the study using a microscope objective. I would say that, for beaten kraft paper, the distribution of stresses about defects was over a broader area than in unbeaten kraft or newsprint.

Prof. P. Luner I would like to ask Dr Moffatt about changes in other properties on calendering besides breaking level. Have you looked at the tear or fold values on calendering newsprint and how these numbers change relative to the breaking level?

Dr J. M. Moffatt We did not really look at those other properties during the course of this study. We undertook these studies from the calendering end and have done a considerable amount of work in the field. When we managed to derive from the results this unique correlation between tensile and minimum caliper experienced during calendering, we did not really pursue the matter much further.

My original draft of this paper went into some of the implications of our work for developing realistic quality control tests for pressroom runnability. I hope it will be published somewhere else at a later date.

Dr Lyne I have a comment on Dr Moffatt's paper along the lines of Prof. Luner's question. In so far as the fracture line is concerned, there is an equating in the text of your paper of the break that occurs in a tensile fracture and the kind of rupture line that occurs in an in-plane tear. I disagree with that. I do not think that you can take your grammage results for a rupture line of a tensile specimen and merely equate it to the kind of ruptured line you would anticipate for an in-plane tear line. Specifically, in the paper that is quoted (your reference 7), we observed that the in-plane tear line deviated around high grammage points (or flocs) in the sheet (on calendered paper as well). I think tear and tensile lines might be different in this respect, because in-plane tear is primarily a matter of local rotation and opening of the web. It would seem logical that the tear line should follow zones that yield most readily—in other words, low grammage zones.

The Chairman What is the effect of the rate of loading?—your tests were presumably conducted in the normal standardised manner. If a fairly long strip of paper is loaded very rapidly, it can break into four or five pieces and I am just wondering along which lines these four or five fractures line would run, high spots or low spots. So far as I know, the theory for this effect—first observed in Stockholm a number of years ago, I think—has been that a standing wave moves through the paper between the two clamps. If the antinodes coincide with weak spots, the strip can break in different places. I wonder if you have given this dynamic fracture process any thought, because this is of course what newsprint is subjected to on the printing machine.

Dr Moffatt Were you using, Dr Lyne, actual newsprint or were you using handsheets? In the published work, if I remember correctly, you were using handsheets. How much calendering did you give the paper?

I expect our next published paper will answer the Chairman's question.

Dr Lyne We had studies in that paper on both TAPPI standard handsheets and on normal production newsprint. The handsheets were not calendered, but the newsprint underwent normal machine calendering. A ciné study of the in-plane tearing of this newsprint showed that the tear line avoided high mass points (or flocs) as it propagated across the web.

Dr A. de Ruvo In understanding formation testing and its relation to mechanical properties and the uniformity of mechanical properties, is it that the more uniform the sheet, the more uniform the mechanical properties? It is important to realise that you have other types of weak link in the structure—in the fibre itself. We need to distinguish when such weak links in the structure become more important than the improvement in formation. We should be provided with some means of measuring or distinguishing between weak links in the fibre material and those in the structure itself.

Dr D. H. Page I do not want to pre-empt what Prof. Axelrad might have to say, but I would like to comment on the interpretation of the interference pattern. It seems to me that the most likely interpretation of these wavy fringes in the middle of the sheet, in contrast to the rather straight fringes near the jaws, is that the sheet is going into longitudinal wrinkles while it is being strained and that these are out-of-plane displacements, which would of course be much larger than the in-plane displacements. If that is so, we would expect the extremely high coefficient of variation in the strain measured in this way, because it is not strictly the strain in the sheet that one is measuring, it is partly the out-of-plane displacement.

I do not know whether this is mentioned anywhere in anything that you have stated, because I have not read it all, but is that interpretation a valid one?

Dr Lyne I gather you have not read the addendum. A calculation of the relative sensitivity to the in-plane and out-of-plane motions with the various experimental set-ups appears in it. You certainly cannot eliminate the out-of-plane element in the procedure that we have used. You can only minimise its effect by choosing a minimum angle β, which we have done. In the experiment you are mentioning, there was a greater sensitivity to in-plane motion. We can say with certainty that the in-plane strain is being reflected in the fringe pattern, but the magnitude of the out-of-plane component is theoretically inestimable for the 10μ (or so) or in-plane strain induced between exposures of the hologram plate, since the paper was strained into the plastic region before the first exposure of the hologram. We have attempted to eliminate macro buckling from entering into our analysis by rejecting holograms that show gross fringe movement. Since we were looking for a general strength uniformity figure for a printing paper, it seemed satisfactory to us that *local* out-of-plane motion should be included in that figure.

Dr Mardon Dr Moffatt, whereas the grammage variations with time in the machine-direction would not have any effect on the significant discovery that you and Mr Beath have made, the grammage variations across the papermachine would certainly have the same effect as the smaller scale variations that you have been investigating. It seems to me—and I would like your comment—that you have in fact produced a very significant argument for automatic backtending.

Dr Moffatt I think I would be in favour of automatic backtending, because the unevenness that you have across the machine is a factor that is quite relevant to pressroom runnability.

In so far as automatic backtending can reduce or eliminate the measurement and integral lags associated with the manual process, the machine-direction variation in locally experienced compression should be attenuated. I would expect this is to be beneficial. Whether automatic backtending can pay for itself in terms of labour saving and reduced chemical pulp use is another problem.

Mr J. A. McLean Normally, with the sheet caliper of calendered newsprint reduced about 0·001 in by the breaker stack, the crushing action at the machine calender is less severe.