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A STUDY OF THE PARAMETERS ASSOCIATED WITH EMPLOYING LASER SPECKLE CORRELATION FRINGES TO MEASURE IN-PLANE STRAIN

FRANK D. ADAMS

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FRANK D. ADAMS

FOREWORD

This report is the result of an in-house effort conducted under Project 1467, "Structural Analysis Methods," Task 146702, "Thermoelastic Structural Analysis Methods."

The work reported herein was conducted from December 1971 to February 1972 by Dr. Frank D. Adams, Physicist in the Analysis Group, Structures Division, Air Force Flight Dynamics Laboratory. Mr. R. M. Bader (AFFDL/FBR) is the Technical Manager of the Analysis Group.

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This manuscript was released by the author in February 1972.

This technical report has been reviewed and is approved.

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ABSTRACT

Basic experimental parameters associated with using laser speckle correlation fringes to measure in-plane strain have been investigated. Equations and inequalities are derived which provide bounding numbers for many of the physical parameters. The feasibility of employing this technique for obtaining in-plane strain data in a microscopic region is shown. This suggests that it may be applicable for studying strain distributions in the vicinity of either a crack or an interference fit fastener.

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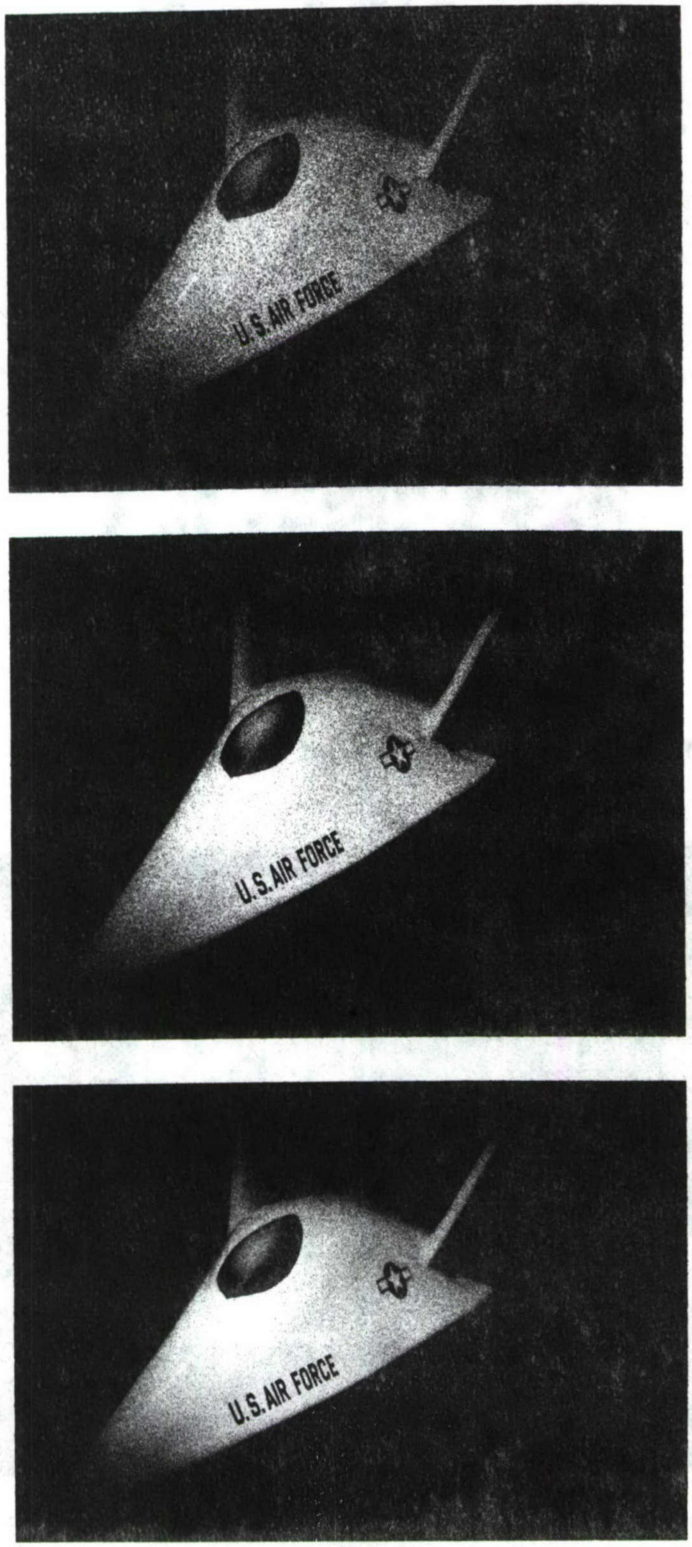
SECTION I
INTRODUCTION

When using coherent laser light for illumination, a uniformly diffuse surface has a speckled or grainy appearance due to random interference within the resolution limit of the eye (or photographic film). This phenomenon is usually an annoyance to a user since it limits the overall resolution in the image field. For example, the fringe pattern in a holographic interferogram becomes difficult to resolve if the mean size of the speckles approaches the fringe width. The speckled appearance of an object illuminated by laser light is illustrated by the photographs in Figure 1. Note that the speckle size is dependent on the lens aperture. A magnified view of the speckle pattern is shown in Figure 2.

In recent years, several researchers have shown that useful information can be extracted from speckle patterns. Leendertz (Reference 1) demonstrated that real-time fringes can be produced using a correlation technique and that this provides a sensitive method of measuring displacements or strains in the surface of an object. Archbold and his colleagues (Reference 2) extended the technique to obtain frozen fringe interferograms. Figure 3 is a photograph taken at the Air Force Flight Dynamics Laboratory Photomechanics Facility which shows real-time fringes generated on a Compact Tension (CT) specimen.

Speckle correlation fringe methods of measuring displacements are comparable in sensitivity to holographic interferometry which can detect movements to less than the wavelength of light. In addition, as with holography, one obtains the "displacement field" in lieu of a set of single point measurements. It should be noted, however, that this method is not a substitute but rather supplements holographic techniques. Although in principle, holographic interferometry may be used to measure three-dimensional displacements, it is not very sensitive for determining the in-plane displacement components and measurement procedures are relatively complicated (Reference 3). On the other hand, the speckle method is most sensitive to an in-plane displacement and can be made almost non-responsive to out-of-plane motion. Thus, general three-dimensional displacements are best resolved by employing a combination of both techniques.

At the Air Force Flight Dynamics Laboratory recent attention has been focused on fracture mechanics. This includes investigation of crack induced structural failures in the vicinity of interference fit fasteners. For this application, the speckle correlation fringe method of measuring in-plane strain is being seriously considered. The purpose of this report is to discuss some of the parameters which control and limit the usefulness of this experimental technique.



Lens Aperture

f/64

f/45

f/32

Figure 1. Speckle Appearance of Model Aircraft Illuminated with Laser Light

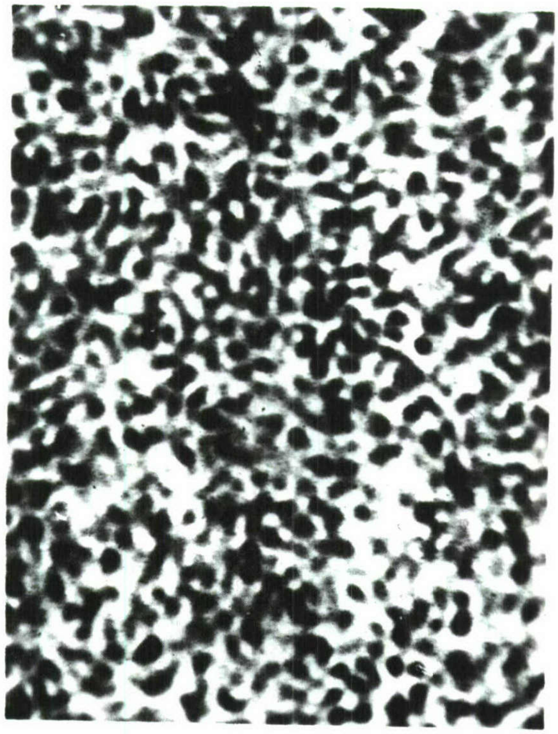


Figure 2. Magnified View of Speckle Pattern

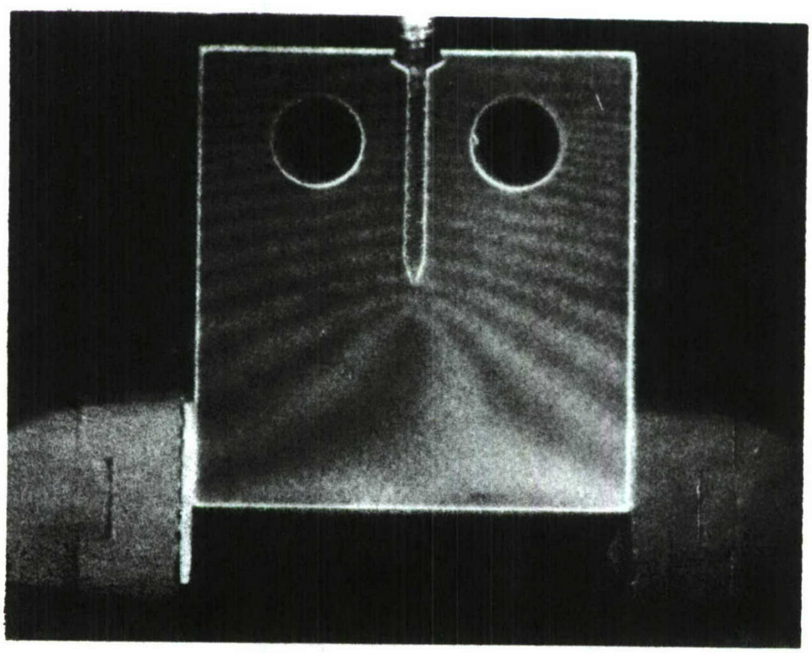


Figure 3. Speckle Correlation Fringes on Compact Tension Specimen

SECTION II

SUMMARY

The basic experimental parameters associated with using speckle correlation fringes for measuring in-plane strain have been investigated. A natural parameter is the quantity $F(M+1)/M$ where F is the ratio of focal length to aperture diameter and M is the magnification of the lens systems. The value of $F(M+1)/M$ must be greater than the number of fringes one expects to observe if reasonable fringe contrast is to be obtained. However, fringe resolution decreases with increasing $F(M+1)/M$, therefore, a practical value is usually bound within a narrow range.

It has been shown that the use of this technique is a feasible approach to obtaining in-plane strain data in a microscopic region and it can be employed in the vicinity of either a crack or an interference fit fastener.

The speckle correlation fringe method supplements holographic interferometry for measuring general three-dimensional displacements.

SECTION III
REVIEW OF THEORY

The following ideas are due originally to Leendertz (Reference 1). Consider a uniformly diffuse surface S(x, y) illuminated with highly coherent laser light. Let $\overline{F_1(x, y)}$ be a complex function representing the amplitude and phase of the light scattered from S and observed at a point P located at some distance from the surface (Figure 4). A bar is used with the function $\overline{F_1(x, y)}$ to denote that the amplitude and phase are average values since any real observation device located at P will have an aperture of non-zero diameter. In fact, the functional form of $\overline{F_1(x, y)}$ depends on the position P, the size of the aperture, as well as the orientation of the illuminating laser beam, but it is a "random" distribution function related to the diffuse surface. A change in any one of the aforementioned three parameters will cause changes in the functional form of $\overline{F_1(x, y)}$. The observed intensity distribution (speckle pattern) is $|\overline{F_1(x, y)}|^2$.

If the laser beam is now divided by a beam splitter and the beams are directed to illuminate the surface from two different angles, the speckle pattern function at P can be represented by $\overline{F_3(x, y)}$ where

$$\overline{F_3(x, y)} = \tfrac{1}{2}\,\overline{F_1(x, y)} + \tfrac{1}{2}\,\overline{F_2(x, y)} \qquad (1)$$

and $\overline{F_2(x, y)}$ is the speckle pattern due to the second beam alone. The detailed amplitude and phase distribution of $\overline{F_3}$ is different from either $\overline{F_1}$ or $\overline{F_2}$, but the statistical properties are the same.

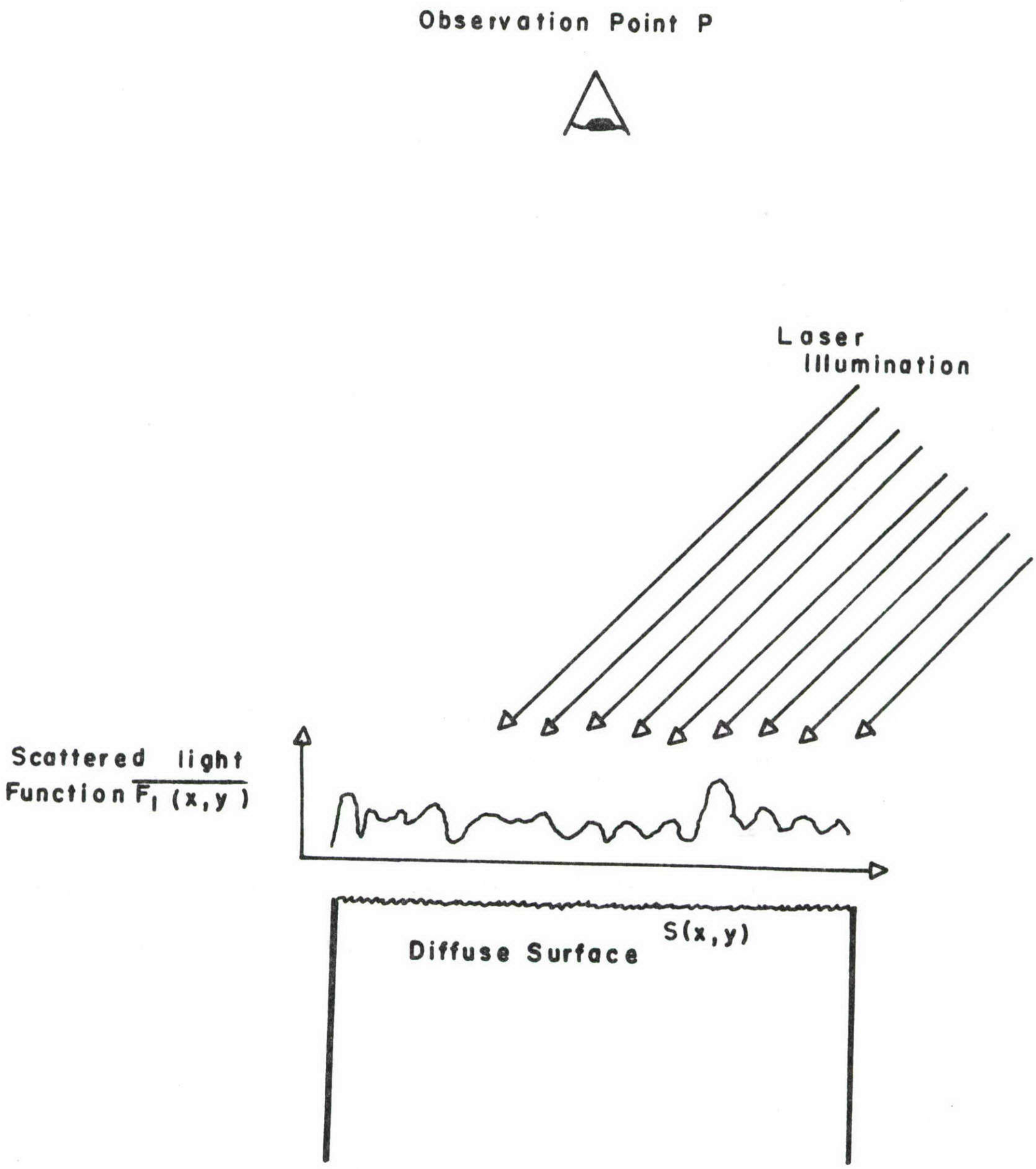


Figure 4. Configuration for Observing Speckle Pattern

The function $\overline{F_3}$ has an interesting feature with respect to the relative phase between the two illumination beams. When the relative phase Δ (path length) between the two beams is changed, the speckle pattern $\overline{F_3}$ also changes. If, however, the phase change Δ is an integral multiple of 2π, $\overline{F_3}$ is found to be unchanged. That is

$$\overline{F_3(o)} = \overline{F_3(2\pi n)} \tag{2}$$

where n is an integer. Leendertz (Reference 1) further showed that the correlation between $\overline{F_3(o)}$ and $\overline{F_3(\Delta)}$ varies with Δ such that it is a minimum where Δ is an odd multiple of π . It is the periodic recovery of correlation expressed in Equation 2 that produces a visible fringe pattern like that shown in Figure 3.

Consider now the simple experimental arrangement shown in Figure 5. Illumination beams 1 and 2 originate from the same laser and are highly coherent. These illuminate the surface from angles θ and $-\theta$ respectively, as measured from the surface normal. Step 1 is to expose the photographic film and record the speckle pattern image on a negative. Step 2 is to develop the negative and replace it exactly so that scattered light from the surface is blocked by the exposed film. The recorded speckle pattern image acts as a rejection filter so that little or no light reaches the eye. A dark image, thus, represents complete correlation of the scattered light with the recorded image. Step 3 is to displace the surface in the x direction by a small amount δ . The relative phase Δ between beams 1 and 2 now change at all points on the surface by

$$\Delta = 4\pi \frac{\delta}{\lambda} \sin\theta \tag{3}$$

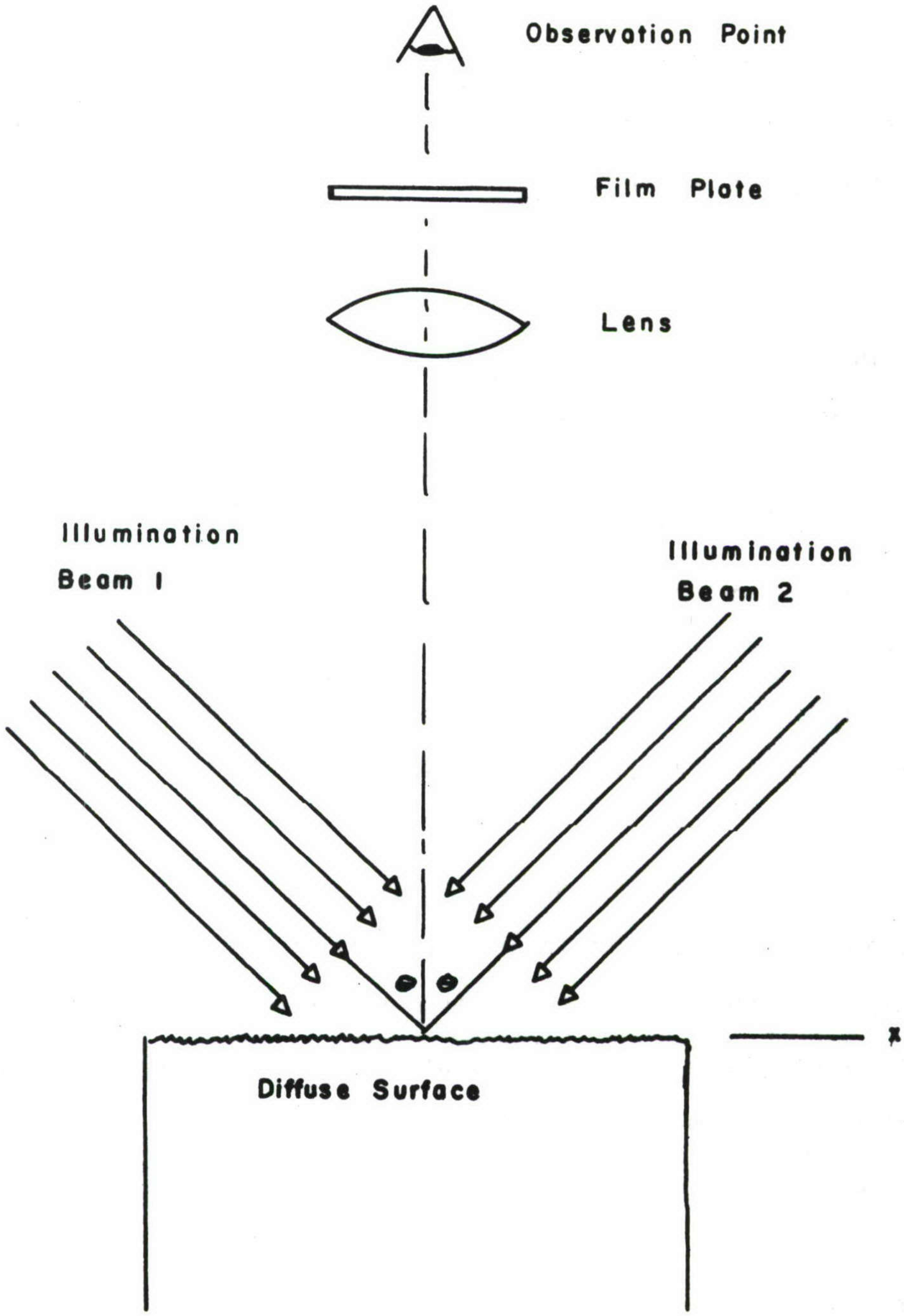


Figure 5. Experimental Configuration for Observing Speckle Correlatior Fringes

where λ is the wavelength of light. If Δ is a multiple of 2π and if the displacement δ is small compared to the mean speckle size, then the correlation of scattered light with the recorded image is maintained. For $\Delta \neq 2\pi n$, a lesser degree of correlation exists and light is transmitted through the photographic negative (the eye observes a brighter image).

If instead of a whole body displacement, the surface is strained, the image will exhibit a periodic fringe pattern which is characteristic of the local displacements. That is a dark fringe (complete correlation) will occur for local displacements which produce a $\Delta = 2\pi n$. A light fringe occurs for local displacements where Δ is an odd multiple of π. Note that Δ is a function only of the x displacement component. The relative phase is not changed by displacements which are normal to the surface or in the in-plane "y" direction.

Speckle correlation fringes are readily observed in real-time or can be photographed through the filter as is the case in Figure 3. Recently, Archbold and his associates obtained frozen fringes in the primary photographic negative by double exposing the film plate before and after the specimen was strained (Reference 2). This method is sensitive to the exposure/development process since it requires exploiting nonlinear characteristics of the recording film to obtain a frozen fringe pattern.

In terms of data reduction procedures, the real-time and double exposure methods are equivalent, except that speckle correlation ($\Delta = 2\pi n$) corresponds to a dark fringe in real-time and a light fringe with the double exposure. It may be noted, however, that the fringe visibility is generally better using the real-time technique.

SECTION IV

A STUDY OF THE BASIC PARAMETERS

From the previous discussion, it is apparent that the speckle correlating fringe method is indeed a sensitive technique for measuring in-plane displacements. The question now is to determine over what range of displacements is the method useful and what are the optimum experimental parameters. In particular, how do the variables associated with the optical and photographic elements in the experimental apparatus affect the measurement technique?

By examining Equation 3, it is apparent that a dark fringe of order n will occur when

$$n\lambda = 2\delta\sin\theta \qquad (4)$$

There are several restrictions which limit the validity of Equation 4. First, displacements on the surface, as measured at the image position (film plate), must be small compared to the mean size of the speckles (Figure 5). The image displacement δ_i is related to the real object displacement by

$$\delta_i = M\delta \qquad (5)$$

where M is the magnification factor of the lens system. An upper limit to the above restriction can be expressed in terms of an inequality

$$\delta_i < \alpha \qquad (6)$$

where α is the mean diameter of speckles on the film plate.

A second restriction is also concerned with the speckle size. If fringes of width d are produced at the film plate position, they must be resolved in the speckle pattern field. Without the use of spatial filters, good visibility will be obtained only if the mean speckle size is smaller than the fringe spacing, that is,

$$d > \alpha \tag{7}$$

A practical lower limit on displacement is secured using Equation 4. Quantitative information is obtained only if one or more fringes are generated, thus

$$\delta > \lambda/(2\sin\theta) \tag{8}$$

is required at least somewhere in the field of view. Note that Equation 8 does not limit the resolution which may be 1/10 or even 1/100 of a fringe width. However, the largest displacement in the field of view is subject to Equation 8 in order that at least one fringe is generated.

All photographic films have limited resolution capabilities usually measured in line pairs per millimeter. If this number is denoted by R, then the following restriction is also applicable:

$$\alpha > 1/R \tag{9}$$

That is, the film must be capable of resolving individual speckles.

The last experimental parameter to be introduced concerns the aperture of the imaging lens system. It is this parameter which, in fact, determines the mean speckle size α . Let us define F as the ratio of focal length to aperture diameter (i.e., F = 5.6 for a stop f/5.6). Then the mean speckle size is determined by the resoultion limit of the lens and is

$$\alpha \simeq 1.2\lambda F(M+1) \qquad (10)$$

Introduced in Equations 4 through 10 is a list of parameters which may be varied to at least some degree by the experimenter. The equations, themselves, reveal the interdependence of these parameters. Our task is to show how these relationships may be used to select optimum experimental parameters and to determine what limitations exist when using this technique.

By combining Equations 5, 6 and 8, we obtain:

$$\lambda/(2\sin\theta) < \delta < \alpha/M \qquad (11)$$

By using Equations 4 and 10, the parameters δ and α may be eliminated and Equation 11 can be rewritten as:

$$1 < n < 2.4[F(M+1)/M]\sin\theta \qquad (12)$$

The left side inequality is just a restatement of the requirement that one or more fringes are necessary to perform meaningful measurements. The right side inequality gives us new information. That is, if we expect to view a fringe of order n, then the quantity $2.4[F(M+1)/M]\sin\theta$ will have to be numerically larger than the fringe order. Except for very small values of θ, a reasonable approximation of Equation 12 is:

$$1 < n < F(M+1)/M \qquad (13)$$

In either case, the quantity $F(M+1)/M$ is a natural parameter for this technique. It is apparent that a large value of F (small aperture) along with a demagnification of the object will favor the visibility of a fringe pattern. When selecting a value of $F(M+1)/M$ one should also keep in mind the fact that n will need to be much larger than unity (maybe 10 or 20) if the experimenter wishes to measure a distribution of displacements such as is the usual case for a strained body.

A large value of F corresponds to large speckle size as related by Equation 10. Therefore, one must examine the selection of $F(M+1)/M$ in terms of the limitations expressed in Equation 7. That is, the speckle size must be kept smaller than the fringe spacing. A rough estimate of the fringe spacing is given by ML/n where L is a linear dimension of the region of interest (assume that the displacement ranges from zero to a maximum value in a length L). By using Equations 7 and 10, one obtains

$$ML/n > 1.2\lambda F(M+1) \tag{14}$$

the wavelength λ can be eliminated by employing Equation 4, hence,

$$F(M+1)/M < (L/\delta) \ / \ (2.4\sin\theta) \tag{15}$$

or approximately

$$F(M+1)/M < L/\delta \tag{16}$$

For the special case of a constant strain, δ/L is the numerical value of the strain. For a more general distribution, δ/L is indicative of the mean strain ε; therefore, we may add another term on Equation 13, and write:

$$1 < n < F(M+1)/M < 1/\varepsilon \tag{17}$$

Finally, since $n > 1$, the maximum displacement in the surface of the object will be larger than λ (see Equation 4) so that $L/\delta < L/\lambda$. Thus, Equation 17 can be further modified to read:

$$1 < n < F(M+1)/M < 1/\varepsilon < L/\lambda \tag{18}$$

Although simple in form, Equation 18 contains a wealth of information. The significance of the two left side inequalities has been discussed previously. The statement, $1/\varepsilon < L/\lambda$ tends to limit the minimum mean strain that can be measured. It also shows that small strains can be resolved only if accumulated over an ample distance so that the total displacement will generate a fringe of at least order one.

The experimental parameter $F(M+1)/M$ is bounded by

$$n < F(M+1)/M < 1/\varepsilon \tag{19}$$

This expression may be utilized in selecting the appropriate optical apparatus and experimental configuration. The individual values of F and M will depend on the resolution capability of the photographic film. From Equations 9 and 10 we may write

$$\cancel{F(M+1) < 1/(\lambda R)} \qquad R > \frac{1}{\lambda F(M+1)} \tag{20}$$

Equations 19 and 20 determine the allowable optical parameters.

It is interesting to note from Equation 18 that we may reasonably expect

$$n < < 1/\varepsilon \tag{21}$$

The selected value of F(M+1)/M places an upper limit on the mean strain (Equation 19). However, Equation 21 provides the limit in a more general way. Since n will necessarily be at least five or ten fringes to resolve a strain distribution, the mean strain will be limited below 10^{-2}. Note that larger values of strain in a local region may still be resolvable and that the more basic limitation concerns accumulated strain or displacement.

Because $1/\varepsilon = L/\delta \approx L/n\lambda$, we may write using Equation 21

$$L >> \lambda\, n^2 \qquad (22)$$

The above equation provides a method of estimating the minimum size region one can examine using the speckle correlation fringe method. A reasonable lower bound is

$$L_{\text{lower bound}} \approx 10\lambda n^2 \qquad (23)$$

For red laser light, $\lambda \approx .63$ μm. If we require as a bare minimum of five fringes to resolve the strain distribution, the lower bound value is L ≈ 150 μm. For ten fringes, a 600 μm lower bound is applicable. In either case, these computations indicate that it is feasible to use speckle correlation fringes for measuring the in-plane strain distribution in a microscopic region. The method may, therefore, be applicable in the vicinity of a small crack or near an interference fit fastener.

Finally, it should be noted that in the previous discussions, many of the inequalities were simplified by assuming that $2\sin\theta$ is numerically close to unity, that is, θ is chosen to not be close to zero. The parameter, θ , determines the sensitivity of the method (number of fringes per unit displacement) as can be seen from examining Equations 12 and 15. One might be tempted to design the measuring apparatus using a small θ in order to desensitize the method and measure larger strains. Be aware, however, that the upper limits on the strain and displacements are not rooted in these equations, but rather come from Equation 6 which is independent of θ . Furthermore, the parameter θ , does not affect the speckle size. Thus, if the film resolution is sufficient to resolve speckles and if the criteria given by Equation 18 are met, then the correlation fringes, which are wider than the speckles, <u>can always be resolved</u>. Thus, convenient values of θ near 30° or 45° will usually be appropriate. One possible exception where a small θ (densensitization) may be useful would be a case where the camera film used to photograph the fringe pattern has an inferior resolution compared to that of the film used to make the correlation filter. In this case, a smaller number of fringes per unit displacement can improve the data in terms of fringe resolution. This technique will not, however, improve the inherent fringe contrast.

For large displacement measurements, it is probably more appropriate to use the double exposure-speckle diffraction fringe technique suggested by Archbold, Burch, and Ennos (Reference 2) rather than desensitize the speckle correlation fringe method discussed in this report. Speckle diffraction fringes are produced only if displacements are larger than a speckle diameter, thus, the two methods supplement each other.

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3. F. D. Adams, and R. R. Corwin, "A Technique for Measuring In-Plane Displacements by Holographic Interferometry." AFFDL-TR-72-5 (February 1972).

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13. ABSTRACT

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