Higher sensitivity moiré interferometry for micromechanics studies

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Abstract. A whole-field in-plane displacement measurement method was developed for micromechanics studies. The method increased the sensitivity of conventional moiré interferometry by an order of magnitude. The increased sensitivity was achieved by a two-step process. Microscopic moiré interferometry, used for step 1 to map an original displacement field, provided a basic sensitivity of 4.8 fringes/μm displacement, which exceeds the previously conceived theoretical limit. Optical/digital fringe multiplication method (ODFMM) was implemented for step 2 to achieve further enhancement of sensitivity. The ODFMM consists of optical fringe shifting and a digital process to sharpen and combine the shifted fringes. The result is a map with β times as many fringe contours as the original map of step 1. A factor of β = 12 was achieved, providing a sensitivity of 57.6 fringes/μm displacement, which corresponds to that of moiré with 57,600 lines per mm (1,463,000 lines per in.). The optical, mechanical, and electronic systems implemented here are remarkably robust and quick. The method is demonstrated by three practical applications: fiber/matrix deformation of a metal/matrix composite, interface strains in a thick 0/90-deg graphite/epoxy composite, and thermal deformation around a solder joint in a microelectronic subassembly.

Subject terms: optical/digital fringe multiplication method; microscopic moiré interferometry; fringe shifting; fringe sharpening; fringe multiplication.

1 Introduction

This research is intended to provide enhanced capabilities for experimental micromechanics analyses. Whole-field contour maps of in-plane displacements \( U \) and \( V \) are desired for microscopic fields of view. Because the relative displacements within a microscopic field can be very small even when strains are large, higher sensitivity is needed to map the displacement fields. The specific objective is an increase of displacement sensitivity by an order of magnitude (compared to the 2.4 fringes/μm displacement sensitivity of conventional moiré interferometry1), in combination with the spatial resolution of the optical microscope.

With moiré interferometry, in-plane \( U \) and \( V \) displacements are calculated from fringe orders \( N_x \) and \( N_y \) by

\[
U = \frac{1}{f} N_x, \quad V = \frac{1}{f} N_y, \quad \frac{1}{f} = g, \tag{1}
\]

where \( f \) and \( g \) are the frequency and pitch, respectively, of a virtual reference grating. Equation (1) defines the measurement sensitivity, i.e., the number of fringes per unit displacement, as \( N_x/U = f \). A theoretical upper limit2 is approached as \( f \) approaches \( 2/\lambda \), where \( \lambda \) is the wavelength of light employed. When relative displacements within a microscopic field of view are very small, the sensitivity is insufficient to generate a reasonable number of fringes. However, increased sensitivity can be achieved by a two-step process.

The two-step process is expressed in Fig. 1. Whereas the whole-field fringe pattern of moiré interferometry follows the intensity versus fringe order relationship of curve \( N \) (step 1), the two-step process transforms the distribution to that of curve \( N^* \) (step 2), which represents narrow dark fringe contours on a bright background. The pattern representing the displacement field exhibits \( \beta \) times as many fringe contours, where \( \beta \) is the fringe multiplication factor. The contour interval is reduced by a factor of \( \beta \), and the sensitivity to displacements is increased by the same factor. The resultant pattern then represents specimen displacements by

\[
U = \frac{N_x^*}{\beta f}, \quad V = \frac{N_y^*}{\beta f}, \tag{2}
\]

where \( N^* \) is the fringe order in the final pattern. The relationship to the basic moiré pattern is \( N^* = \beta N + k \), where \( k \) is a constant for the whole field. As in all moiré analyses for deformation studies, rigid-body displacements are inconsequential, and the location of a point of \( N^* = 0 \) is arbitrary.

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In this work, microscopic moiré interferometry was used for step 1 to map an original displacement field. It provided a basic sensitivity of 4.8 fringes/μm displacement. Its reciprocal, the contour interval, was 208 nm displacement per fringe order. A fringe multiplication method was implemented for step 2. In the method, an automatic fringe-shifting scheme was employed to record a sequence of β-shifted fringe patterns, each shifted by a phase increment of $2\pi/\beta$. The series of shifted patterns was sharpened and combined into a single contour map. Fringe sharpening was necessary because the width of fringes limits the number of patterns in the composite map. Digital image processing produced very thin fringe contours. Then, shifted and sharpened patterns were combined to create the contour maps of $N^\alpha$ and $N^\beta$. The method is called the optical/digital fringe multiplication method (ODFMM). Multiplication patterns with $\beta = 12$ were achieved, providing a displacement sensitivity of 57.6 fringes/μm displacement, or a contour interval of 17.4 nm per fringe contour. The techniques used to achieve these results are described in the body of the paper.

2 Microscopic Moiré Interferometry

A microscopic moiré interferometry technique was employed for step 1 to map an original displacement field, wherein an immersion interferometer was used with a microscope and CCD video camera. The complete optical and mechanical arrangement is illustrated in Fig. 2(a) and described in Ref. 3. The two channels for $U$ and $V$ fields are illustrated in Fig. 2(b). Figure 2(c) is a schematic diagram that shows the optical paths in the immersion interferometer. The basic sensitivity provided by the interferometer was 4.8 fringes/μm, which exceeds the previously conceived theoretical limit. This was accomplished by creating a virtual reference grating inside a refractive medium. Thus, the wavelength of light was reduced by the index of refraction, and this reduction enabled the formation of a virtual reference grating of 4800 lines/mm. The configuration of the interferometer made it inherently stable and relatively insensitive to environmental disturbances. This allowed a robust scheme to shift the fringes for step 2.

3 Fringe Shifting

3.1 Fringe-Shifting Scheme

Fringes can be shifted by translating the virtual reference grating relative to the specimen grating. Figure 2(c) explains the fringe-shifting scheme. When the interferometer is translated horizontally by $g/\beta$ (a fraction of the pitch of the virtual reference grating), then the relative change of path lengths of the two beams ($A$ and $B$) is the same fraction of the wavelength, $4\lambda/\beta$. Translation by $g/\beta$ causes a relative retardation of $\lambda/\beta$, and therefore a phase shift of $2\pi/\beta$. Interference of emergent beams $A$ and $B$ produces a moiré pattern of intensity

$$I(x,y) = I_A(x,y) + I_B(x,y)$$

$$+ 2[I_A(x,y)I_B(x,y)]^{1/2} \cos \left(\phi(x,y) + \frac{2\pi}{\beta}\right),$$

where $I$ is the intensity distribution of the moiré pattern, $I_A$ and $I_B$ are the intensities of the two beams that produce the moiré pattern, $\phi$ is the angular phase difference of the two beams caused by deformation of the specimen, and $2\pi/\beta$ is the additional phase difference caused by translation $g/\beta$ of
the interferometer. The phase $\phi$ represents the fringe order $N$ at each point of the moiré pattern by

$$\phi(x, y) = 2\pi N(x, y).$$

The phase and fringe order are fixed values at each $x, y$ point; they are always the values in the original or unshifted moiré pattern.

A translation of $g/\beta$ changes the intensity over the entire field. A series of translations of

$$0, \frac{g}{\beta}, \frac{2g}{\beta}, \frac{3g}{\beta}, \ldots, \frac{(\beta - 1)g}{\beta}$$

produces $\beta$ different intensity patterns, each systematically related to its neighbors by a phase shift of $2\pi/\beta$. Note that the distribution of displacements throughout the field is imbedded in $\phi(x, y)$ and $N(x, y)$ and remains independent of fringe shifting, whereas the positions of the intensity maxima and minima are altered by fringe shifting.

Figure 3(a) illustrates the physical shape of the translation device and the immersion interferometer. The displacement generated by the piezoelectric actuator deflects the flexible arms of the actuator holder. This deflection translates the interferometer with respect to the specimen grating, as illustrated in Fig. 3(b), where the deflection is much exaggerated. Since the direction of motion is 45 deg from the $x$ and $y$ axes of the specimen, a displacement of $(2)^{\frac{1}{2}}g/\beta$ is required for each fringe shift. The calibrations for fringe shifting of the $U$ and $V$ fields were identical.

### 3.2 Calibration

The apparatus was calibrated by a closed-loop system. Its block diagram is illustrated in Fig. 4. The system consists of a piezoelectric actuator, digital-to-analog (D/A) converter, programmable DC amplifier, and hardware components for image processing. The piezoelectric actuator used here operates in a high voltage range (0 to 1000 V) and its maximum traveling distance is 5 $\mu$m. Although a traveling distance of less than 1 $\mu$m was actually required, the larger maximum traveling distance allowed use of the actuator near the center of its traveling range. This avoids nonlinearity and hysteresis. A D/A converter board was installed in a personal computer to generate 0- to 5-V analog output. The analog output provided the input for a programmable DC amplifier, which amplifies the small voltage input to the desired voltage level for the piezoelectric actuator. The resolution of the system was governed by the resolution of the D/A converter, which has 12-bit resolution to yield an error bound of $\pm 1.22$ mV in the output signal. The programmable DC amplifier has two useful features, a DC bias of 0 to 1000 V and a variable gain of 0 to 200. In the calibration, the DC bias was set at 450 V, and a gain of about 30 was used. The final error bound of the voltage output after being amplified was $\pm 37$ mV, which is the error bound for the D/A converter multiplied by the gain used. This corresponds to an error of less than $\pm 0.2$ nm in the traveling distance of the actuator and less than $\pm 0.15$ nm in the $x$ and $y$ directions. The overall error of the translation system is slightly greater.

The calibration was performed in two steps, initial and fine calibration. In the initial calibration, the desired input voltage was specified and the variable gain was slowly increased until a shifted fringe was superposed onto the original pattern (a phase shift of $2\pi$). Thereafter, the gain remained fixed. In the fine calibration, the original image was captured and digitized. Then, the shifting voltage for the phase shift of $2\pi$ was input and the shifted image was also captured and digitized. The original image was subtracted from the shifted one and the process was repeated with slightly changed shifting voltages as input until the subtracted images became null, that is, when the two images were identically the same.

Subsequently, a series of fringe-shifted patterns were captured and digitized with phase shift increments of $2\pi/\beta$. Excellent linearity and repeatability of the fringe shifting was achieved after the calibration, as evidenced by tests using rigid-body rotation of the specimen. Because it takes only $1/30$ s to digitize one frame ($480 \times 480$ pixel format),
shifting and grabbing a series of shifted patterns is accomplished within a fraction of a second.

4 Fringe Sharpening and Multiplication

A series of moiré patterns are obtained by sequential shifts of the immersion interferometer by a constant increment \( g/\beta \), where \( \beta \) is a fringe multiplication factor; \( \beta \) is an even integer. The intensity distributions of the moiré fringes are shifted sequentially by phase shifts of \( 2\pi/\beta \). These sets of optical data are recorded and transformed into an array of sharpened fringe contours by digital image processing.

4.1 Fringe-Sharpening Algorithm

Since \( \beta \) is an even integer, the series of \( \beta \) moiré patterns can be divided into two groups: the patterns of the first half and their complements. The intensity distributions of these patterns can be expressed as

\[
I_i(x,y) = I_A(x,y) + I_B(x,y) + 2[I_A(x,y)I_B(x,y)]^{1/2} \cos \left( \phi(x,y) + \frac{2i\pi}{\beta} \right),
\]

\[
I_i^R(x,y) = I_A(x,y) + I_B(x,y) - 2[I_A(x,y)I_B(x,y)]^{1/2} \cos \left( \phi(x,y) + \frac{2i\pi}{\beta} \right),
\]

\( i = 0, 1, \ldots, \beta/2 - 1 \),

where \( I_i \) is the intensity distribution of the \( i \)'th shifted pattern, which is shifted by \( 2ir/\beta \) with respect to the original pattern, and \( I_i^R \) is the intensity distribution of the corresponding complementary pattern, which is shifted by \( \pi \) with respect to the \( i \)'th shifted pattern.

When these intensity distributions are captured by a video camera and the intensities at every pixel are converted to digital form, they can be subtracted to give the resulting intensity distribution as

\[
I_r(x,y) = I_i(x,y) - I_i^R(x,y) = 4[I_A(x,y)I_B(x,y)]^{1/2} \cos \left( \phi(x,y) + \frac{2i\pi}{\beta} \right),
\]

which shows that the resulting intensity is a cosine curve modulated by a term containing two input beams. Equation (6) indicates that at the points where the phase \( \phi(x,y) \) satisfies the condition \( \cos[\phi(x,y) + 2i\pi/\beta] = 0 \), the phase is independent of both \( I_A \) and \( I_B \) and is, therefore, independent of systematic noise in \( I_A \) and \( I_B \). These phase values can be expressed as

\[
\phi(x,y) = \pi \left( \frac{2m + 1}{2} \pm \frac{2i}{\beta} \right), \quad m = 0, \pm 1, \pm 2, \ldots.
\]

Thus, \( I_r \) = 0 at every point where, from Eq. (4),

\[
N(x,y) = \frac{2m + 1}{4} - \frac{i}{\beta}.
\]

The fringe-shifting algorithm continues by inverting negative intensity values and binarizing by truncation near \( I_r = 0 \).

Narrow black contours occur in the whole-field map where \( N(x,y) \) in the original pattern has the fractional fringe order values prescribed by Eq. (8). A set of such fringe contours is formed for each \( i \) value.

Figure 5 illustrates these equations and shows that the points of fractional fringe orders \( N(x,y) \) in Eq. (8) can be determined accurately without regard to the nonuniform illumination or the optical noise that is contained in the input beams. Figure 5(a) illustrates the intensity distributions of the original moiré pattern and its complement. The uppermost curve, shown here as an envelope, represents the intensity distribution when constructive interference occurs everywhere in the field. Its variation represents low-frequency and high-frequency noise. This intensity can be considered invariant. It is modulated at each point in proportion to the idealized (or zero-noise) intensity distribution of each moiré pattern. Accordingly, the noise appears in the curves of \( I \) and \( I^R \) [Fig. 5(a)], but attenuated in proportion to the intensity level in the idealized moiré pattern. Consequently, the contribution of noise is identical wherever \( I = I^R \), and unequal elsewhere. Thus, the noise does not influence the locations of the points of intersection of these curves. After subtraction, the curves of Fig. 5(b) cross the zero-intensity axis at the correct points, independent of optical noise, as prescribed by Eqs. (6) through (8). These crossings are points of fractional fringe orders defined by Eq. (8). They occur at quarter fringe-order points \( [i.e., N(x,y) = 1/4, 3/4, 5/4, \ldots] \) and are called quarter points.

The next step is represented in Fig. 5(c), where the negative portions of the curve are inverted by taking the absolute value of \( I_r \). This produces highly sharpened contours at the quarter points, where \( |I_r(x,y)| = 0 \). As a final step in ma-
Manipulating the data, the intensities are binarized by truncation near $|I_r(x,y)| = 0$. The result is the intensity distribution of Fig. 5(d), which represents a bright background with two narrow dark fringes for each fringe of the original moiré pattern.

The process is illustrated in Fig. 6 on a whole-field basis. The original moiré pattern and its $\pi$-shifted complement are shown as $I$ and $I'$. Optical noise is evident in both patterns. Although the patterns were recorded with a 256-gray-level capacity, they were printed out in only a few gray levels. The sequence in Fig. 6 continues with the double-frequency plot corresponding to Fig. 5(c) and then the same distribution after truncation. The result is a plot of highly sharpened fractional fringe contours, basically free of noise.

The idea of subtraction [Fig. 5(b)] can be found in Refs. 6 through 8. The algorithms employed here to locate fringe contours after subtraction are less complicated than those of Ref. 8. References 6 and 7 investigated homogeneous displacements, and fringe contours were not required.

**4.2 Fringe Multiplication**

Fringe multiplication by a multiplication factor $\beta$ can be accomplished by combining all the fractional fringe contours. As an example, consider the case of $\beta = 6$, illustrated in Fig. 7. The zeroth shifted (original) moiré pattern and its complement (third shifted pattern), represented by $I_0$ and $I_3$, produce sharpened fringe contours where $N = 1/4$, $3/4$, $5/4$, $7/4$, ... $N = 1/6$.

The first shifted and complementary (fourth shifted) patterns produce sharpened contours where $N = 1/12$, $7/12$, $11/12$, ... [Fig. 7(b)]. Finally, the second shifted pattern and its complement (fifth shifted pattern) produce sharpened contours at fractional fringe orders $N = 5/12$, $11/12$, ... [Fig. 7(c)]. These fractional fringe contours are combined (by the fringe sharpening and multiplication algorithm) into a composite contour map, which exhibits six fringe contours for each fringe in the basic moiré pattern [Fig. 7(d)]. The six fringe contours are separated by equal fringe-order increments of $\Delta N = 1/6$.

If rigid-body displacements are dismissed and fringe orders $N^*$ are assigned to the combined pattern in the normal way, the patterns represent $U$ and $V$ displacements by Eq. (2), repeated here,

$$U = \frac{N^*}{\beta f}, \quad V = \frac{N^*}{\beta f}.$$  

The fringe multiplication factor $\beta$ is equal to the number of moiré patterns (original and shifted) utilized to create the combined contour map.

**4.3 Displacement Sensitivity and Resolution**

The $N^*$ contour maps provide a sensitivity of $\beta f$ fringes per unit displacement. The contour interval is $1/\beta f$ displacement per fringe contour. The sensitivity is increased by a factor...
of $\beta$, compared to the sensitivity of the basic moiré pattern represented by $I_0$ in Fig. 7. The displacement resolution is the smallest displacement that can be inferred reliably from the contour map. In engineering practice, interpolation between contours to 1/5 or 1/10 of the contour interval is usually accepted as reliable. Thus, the displacement resolution is 1/5 or 1/10 of $g/\beta$ (or 1/10$\beta$ divided by 5 or 10).

5 Applications

5.1 Deformation of a Metal/Matrix Composite

In this demonstration, the specimen material was a composite of silicon-carbide fibers in an aluminum matrix. The 0-deg fibers were perpendicular to the cross section, as illustrated in Fig. 8. A specimen grating was replicated on the face and the specimen was loaded in compression. The specimen was subjected to a large load, which incurred plastic deformations in the ductile aluminum matrix. Fringe patterns depicting the $V$ and $U$ displacement fields are shown in Fig. 8, where the contour interval is 52 nm per fringe contour. Significant normal and shear strain concentrations are observed in the aluminum matrix.

5.2 Normal Strains across an Interface in a Thick Graphite/Epoxy Composite

The micromechanical behavior at a 0/90-deg interface of a thick, cross-ply graphite/epoxy composite laminate was investigated. The specimen was loaded in interlaminar compression and the deformation normal to the ply interface was documented. Figure 9 illustrates the specimen, which was cut from a thick-walled cylinder. The $xyz$ coordinates correspond to the radial, axial, and hoop directions of the cylinder, respectively. The specimen ends were ground flat and blocks of the same material were attached to extend the specimen height. This was done to minimize the influence of friction forces generated between the loading platens and the composite specimen. The specimen grating was replicated on face $A$ (the $xy$ plane) and the deformation of the face was observed.

Figure 9(a) depicts the longitudinal or $V$-displacement field of face $A$ with a contour interval of 104 nm per fringe contour ($\beta = 2$). The fringe gradient (which represents the normal strain $\varepsilon_y$) is greater in the 90-deg ply than in the 0-deg ply. The carrier fringe technique was used to transform the displacement field to that illustrated in Fig. 9(b). Here, a uniform normal strain was subtracted by carrier fringes of extension so that the sign of the fringe gradient at the 0-deg ply becomes opposite to that at the 90-deg ply; in addition, carrier fringes of rotation were used to obtain continuous fringes across the interface. The slope of the fringes relates to the strain $\varepsilon_y$. The extremely rapid change of slope near the interface indicates a severe $\varepsilon_y$ strain gradient.

Note that subtraction of the uniform part of the displacement field transformed the fringe pattern to a very sparse pattern, with few fringe contours. Accordingly, a higher sensitivity was required to document the displacement field. In Fig. 9(b), the sensitivity was increased by another factor of 4. The fringe multiplication factor is $\beta = 8$ and the contour interval is 26 nm per fringe contour.

The strain distribution along $A-A'$ is plotted in Fig. 9(c). The normal strains $\varepsilon_y$ in each ply become increasingly dissimilar as they approach the interface, but then the curves turn around and join. The result is a very large $\varepsilon_y$ strain gradient near the interface. The dramatic strain gradient at the interface is ascribed to a free-surface effect in composites wherein constraints that exist in the interior of a body vanish or relax near free surfaces.
5.3 Thermal Deformation of a Microelectronic Assembly

The solder ball interconnection is widely used for assembly of computer chips to ceramic substrates, as illustrated in Fig. 10. When the assembly is subjected to thermal cycles in its normal operation, the thermal expansion mismatch between the chip and substrate creates deformations and stresses at each solder joint. These lead to electrical and mechanical fatigue failures. An epoxy resin with a coefficient of thermal expansion similar to that of the solder can be used to improve the condition by reducing thermal strains in the solder balls. The deformation of this type of package is illustrated.

The experimental procedure for determining steady state thermal strains by moiré interferometry is reported in Ref. 10. Briefly, a special grating mold is produced on a zero-expansion substrate so that it has the same frequency at room temperature and elevated temperature. This mold is used to replicate a specimen grating at elevated temperature. This mold is also used to adjust the frequency of the virtual reference grating at room temperature. Then, the deformation of the specimen and specimen grating is observed at room temperature. Thus, the absolute change of specimen grating frequency, induced by cooling the specimen, is recorded in the moiré pattern.

The $V$ and $U$ displacements induced by $\Delta T$ of 62°C are depicted in Fig. 10. The fringe multiplication factor is $\beta = 12$ and the contour interval is 17 nm per fringe contour. Although the location of the solder ball is evident in both fields, the presence of the epoxy encapsulant eliminates the serious shear strain concentrations that would otherwise occur at the solder joint. In Fig. 10(a), the closely spaced fringes in the epoxy resin represent the thermal expansion of the epoxy and solder ball normal to the chip surface, but the corresponding thermal expansion parallel to the chip [Fig. 10(b)] is restrained by the mating parts. Only tiny shears are developed. The normal stresses $\sigma_x$ and $\sigma_y$ in each material depend on the measured strains minus that from free thermal expansion in the respective material. However, shear stresses $\tau_{xy}$ are proportional to the measured shear strains, independent of the free thermal expansion strains.
Si Chip  
Solder  
Epoxy Resin  
Ball  
Ceramic Substrate  
Microelectronic Assembly  
Thermal Strains  
$\Delta T = 62^\circ C$

Fig. 10 (a) $N_x$ or $V$ field and (b) $N_y$ or $U$ field around a solder joint in a microelectronic subassembly.

6 Discussion

6.1 Nonharmonic Intensity Distributions and Linearity

The fringe-sharpening algorithm consists of these operations:

- digitize the intensities at each pixel for a moiré pattern and its $\pi$-shifted pattern
- subtract these intensity values at each pixel
- multiply negative values by $-1$
- binarize by truncation near $I = 0$
- plot locations of zero values.

Although the algorithm was described in Sec. 4.1 for the special case of a harmonic (or cosinusoidal) distribution of intensity versus fringe order, it is actually much more general and powerful. Figure 11 illustrates the generalization. Wherever $I = I^m$ (i.e., wherever $I - I^m = 0$), the algorithm generates a sharpened fringe. This applies for a great variety of cyclic functions of $I$ versus $N$, as illustrated in Fig. 11.

As a corollary, linearity of the video camera system is not required for accurate results. The positions of sharpened fringes remain independent of distortions of the intensity distribution caused by camera nonlinearity. This feature, coupled with the inherent cancellation of optical noise where $I = I^m$, permits a substantial economy in instrumentation costs.

6.2 Comparison

The optical/digital fringe multiplication method (ODFMM) proposed here should be compared to the quasiheterodyne (or phase-stepping) method, which is well known and com-
monly utilized for analysis of interferograms. There are advantages and disadvantages of both. The quasiheterodyne method computes the fringe order at every pixel in the field, whereas the ODFMM provides a contour map with discrete contour intervals. As a consequence, the quasiheterodyne method is much more computer intensive. With the quasiheterodyne method the results of these extensive computations are frequently displayed in the form of a contour map, thus reducing the importance of the information available at pixels between the contours.

The quasiheterodyne method is critically dependent on the harmonic intensity distribution. Although many interferometers produce two-beam interference and faithful harmonic distributions, the requirement precludes certain applications involving multiple-beam interference. Examples include Fizeau interferometry (when reflectivity is not small) and geometric moiré systems (filtering techniques to suppress higher harmonics have been used for such applications). Perhaps more importantly, the requirement prescribes stringent conditions on linearity of the image-recording system.

A factor that favors the reliability of the ODFMM lies in the distribution of data sites. With the ODFMM, all the data that is utilized lies at the quarter points, where the gradient of the intensity versus fringe order (or phase) curve is the largest. On the other hand, with the quasiheterodyne method, some of the data will usually lie in the low-gradient region (near intensity minima or maxima) where the phase angle changes rapidly with changes of intensity. The difference is impressive. The phase increment corresponding to a 256-step gray scale is 32 times larger at intensity maxima and minima, compared to the increment at the quarter points. In practice, fewer than 256 gray levels are used, and the ratio is larger than 32:1. Thus, the accuracy of phase data used in the quasiheterodyne method is diminished. This advantage of data sites is emphasized in Ref. 6.

The displacement resolution of the quasiheterodyne method is often given as 1/100 of a fringe. With the contour interval of 208 nm/fringe order achieved here, this corresponds to a resolution of 2 nm. With the ODFMM, a contour interval of 17 nm/fringe contour was demonstrated and interpolation between contours to 2 nm is practical. The resolutions are essentially equal. Regarding this extra operation, interpolation by local curve-fitting schemes is not computer intensive, and furthermore, it is equivalent to a curve-smoothing operation that would be required in many cases as a step of the quasiheterodyne method.

6.3 Grating Thickness

Another factor relating to practical application of the method to micromechanics is the thickness of the specimen grating. For macroscopic interferometry, the usual replication technique produces a grating thickness of about 25 μm. Whereas the deformation of the specimen surface is sought, the deformation on the outside surface of the grating is actually observed and measured. The difference is negligible for most problems, but in some micromechanics studies where strain gradients are very large, it could be significant. Shear lag through the thickness of the grating could mask the true displacement behavior in zones of abrupt changes or discontinuities of displacements. In this work, the replication technique was improved to reduce the specimen grating thickness by an order of magnitude. For the small fields of view encountered in micromechanics studies, the thickness of the specimen grating was reduced to 2 μm, which is slightly smaller than the spatial resolution of the imaging system employed here. Accordingly, the width of the shear lag region is approximately the same as the spatial resolution and a further reduction of grating thickness is unimportant.

7 Conclusions

A whole-field in-plane displacement measurement method was developed for micromechanics studies. The development included use of microscopic moiré interferometry with enhanced sensitivity and development of an automatic fringe-shifting and fringe-sharpening scheme for fringe multiplication—the optical/digital fringe multiplication method.

With the enhanced basic sensitivity of 4.8 fringes/μm displacement, and a fringe multiplication factor of 12, a contour interval of 17 nm per fringe contour was achieved. This corresponds to the sensitivity of moiré with 57,600 lines per mm (1,463,000 lines per in.). The displacement resolution is equal to that of the quasiheterodyne method, but nevertheless, requirements on instrumentation are greatly relaxed. The method is not computer intensive and use of a personal computer is practical.

The method was demonstrated for diverse micromechanical problems of current importance. The development is ideally suited for the study of a broad range of problems in micromechanics, providing an extremely robust system for higher sensitivity deformation measurements.

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References


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