Interferometric Strain/Slope Rosette for Static and Dynamic Measurements

by K. Li

ABSTRACT—The interferometric strain/slope rosette (ISSR) is extended from the interferometric strain gage (ISG) and the interferometric strain rosette (ISR) for measuring three derivatives of out-of-plane displacements in addition to three derivatives of in-plane displacements. The ISSR can be used for both static and dynamic measurements. The principle of the measurement is a combination of diffraction and interference of laser beams. The miniature ISSR is applicable to complex geometries that are unaccessible to conventional sensors. As six displacement derivatives are measured, components of a strain tensor and rotation can be determined. The principle and image-processing system are described. Sensitivities to rigid-body translations are thoroughly studied. The technique is noncontacting, in contrast to resistance strain gages and accelerometers, which require attachment of transducers to specimen surfaces.

Introduction

From the early 1960s, an explosion of optical measuring techniques in science and engineering has emerged with the advent of laser. Optical methods for studying stress/strain in mechanical structures under static and dynamic loadings include holographic, speckle and moiré interferometry, and optical strain gages. They have surpassed the conventional methods with high resolution, high sensitivity and noncontacting nature. The literature covering optical measuring techniques is quite broad. Holographic, speckle and moiré interferometry methods are used to measure full-field displacements and strains, but their frequency responses are limited with the large amount of image processing. Optical strain gages are used to measure local strains, and have potentials to measure dynamic strains and vibrations at high frequencies.

Optical strain gages, which measure strain/displacement at a point, are based on optical interference and diffraction. Two Fabry-Perot interferometer plates were clamped to a specimen for measuring strain by Vose. Bell used a diffraction grating of equally spaced parallel lines ruled on the surface of a specimen. Pryor and North used a single-slit aperture attached to a specimen. The strain measuring principle of these methods is diffraction of light from the spacings between the interferometer plates, the diffraction gratings, and the single-slit aperture. By measuring the change of the diffraction patterns, the strain component related to the change in the width of the slits and gratings can be measured. The interferometric strain gage (ISG) developed by Sharpe is based on interference of laser beams reflected from two grooves on a specimen surface. Applications of the ISG over the past 30 years include studies of elastoplastic behavior, fatigue/creep, fracture mechanics, and mechanical properties of materials and structures with complex geometries at elevated and high temperatures. Li has recently extended the ISG to the interferometric strain rosette (ISR). An ISR contains three microindentations, each with six or eight facets. Three pairs of ISR indentations permit an evaluation of three strain components in the directions of the indentation separations. Thus, the principal strains and principal direction can be obtained.

In this paper, the ISR is further extended to measure three derivatives of out-of-plane displacements. Since the derivatives of out-of-plane displacements are equivalent to the slopes of surface deflections, the technique will be called the interferometric strain/slope rosette (ISSR). Now that six components of displacement derivatives are measured, components of a strain tensor and rotation may be determined. This paper will discuss the principle of applying the technique to measure the strain and rotation components. The ISSR possesses several good features compared with a resistance strain rosette. For example, dynamic response of a resistance strain gage depends on the speed of strain transmission from the specimen to the gage along its thickness and length. Having short gage length (~ 100 μm) and being directly depressed into the specimen surface, the ISSR indentations require essentially zero time for transmission of the dynamic deformation signals. In addition, the ISSR is applicable to large strain and strain cycling, and is insensitive to environmental effects such as moisture, humidity, hydrostatic pressure, nuclear radiation and high temperature. When the ISSR is used for vibration measurements, it comprises several unique characteristics. In a conventional vibration experiment, an accelerometer requires an attachment of a sensor to the specimen, which adds weight and alters the dynamic behavior. The ISSR is noncontacting and does not have a reinforcing effect on the vibrating specimen. Most importantly, the ISSR directly measures out-of-plane slopes, while an accelerometer indirectly measures displacements through an integration of the acceleration, which magnifies error signals and reduces accuracy. Neither a resistance strain rosette nor an accelerator can measure both in-plane and out-of-plane deformations. The ISSR provides a unique experimental mean of studying both dynamic in-plane strains and vibrational out-of-plane slopes simultaneously.
Principle of the Interferometric Strain/Slope Rosette

The ISSR indentations are the same as those of an ISR. An ISSR consists of three microindentations depressed on a specimen surface and can be of two separate configurations. A delta or the so-called 60-deg ISSR contains three six-facet indentations. The three indentations are located at the vertices of an equilateral triangle to form three strain gages in the directions of 0-deg, 60-deg, and 120-deg. A right triangular or the so-called 45-deg ISSR contains three eight-facet indentations that can be grouped to three pairs and define three strain gages in the directions of 0-deg, 90-deg, and 45-deg (Fig. 1). The size of the indentations currently used in the laboratory ranges from 10 to 70 µm, and the indentation separation ranges from 50 to 350 µm. The ISSR indentations are depressed into a specimen surface using a microhardness tester (LECO M-400). The microhardness tester has an X-Y stage and a rotatable eyepiece, which allow positioning of each indentation within a few micrometers. The diamond indenters used to make the ISSR indentations are specially machined to possess six or eight facets with a 136-deg angle between opposite facets. When the ISSR indentations are made, the size and the separation can be controlled, and they must be small enough to create appreciable diffraction and interference from an incident laser beam.

Upon an incident laser beam, each triangular facet in an ISSR indentation reflects and diffracts the laser light and forms a triangular diffraction pattern. The maximum light intensity is in the reflecting direction. The baseline of the triangular pattern is corresponding to the diffraction from the base of the triangular facet in the indentation. The diffraction patterns from a corresponding pair of facets in two indentations overlap to create a pair of Young’s interference fringe patterns. The joining line of the two patterns is coplanar with the joining line of the two indentations. The orientation of the linear fringes is perpendicular to the joining line of the two indentations. For the 60-deg ISSR indentations, three pairs of interference fringe patterns are orientated symmetrically at 60-deg angle to one another. All patterns at the same distance from the ISSR are identical, and each has three groups of linear fringes intersected at 60-deg. The three pairs of the 45-deg ISSR indentations create eight patterns in the directions of 0-deg, 90-deg, 45-deg, and 135-deg. Figure 2 shows the interference fringe patterns of a 45-deg ISSR with 65 µm wide and 150 µm apart indentations. The fringe pattern in the 0-deg or 90-deg directions contains three groups of fringes that are oriented parallel, perpendicular and 45-deg or 135-deg, respectively, to the baseline of the triangular pattern [Fig. 2(a) and (b)]. The fringe patterns in the 45-deg direction contains three groups of fringes that are oriented parallel, 45-deg and 135-deg to the baseline of the triangular pattern. [Fig. 2(c)]. The fringe pattern in the 135-deg direction contains three groups of the fringes oriented perpendicular, 45-deg and 135-deg to the baseline of the triangular pattern [Fig. 2(d)]. Only the three pairs of patterns in the 0-deg, 90-deg, and 45-deg directions, which are coplanar with the corresponding strain gage directions, are used for strain/slope measurements.

Figure 3 is a schematic diagram of the interference principle of two laser beams reflected from a pair of ISSR indentations for strain and slope measurements with respect to the gage direction. The opposite facets in each indentation reflect the incident laser beam into two directions at ±θ angles from the incident laser beam. The diffraction patterns from the two indentations overlap to create interference fringe patterns 1 and 2. The intensity of the pattern can be expressed as

$$I = 4A^2 \sin^2 \beta / \beta^2 \cos^2 \Phi, \Phi = \pi \lambda / A, \beta = \sin \beta / \sin \phi,$$

where $4A^2$ is the value of the maximum intensity at the center of the pattern, β is the phase angle of diffraction and $\sin^2 \beta / \beta^2$ defines the envelop of the diffraction pattern within which the interference fringes are superimposed, λ is wavelength of the laser light, Δ is the path length difference between the interfering laser beams and Φ is the phase angle of interference. Bright fringes occur when $Φ = ±m\pi$ and $Δ = ±m\lambda, m = 0, 1, 2, 3, \ldots$, while the dark fringes occur when $Φ = ±(m+1/2)\pi$ and $Δ = ±(m+1/2)\lambda, m = 0, 1, 2, 3, \ldots$.

When the specimen is deformed, the two indentation points move from $P_1(0,0,0)$ and $P_2(d,0,0)$ to $P_1(u,v,w)$ and $P_2(d+u+\delta u, v+\delta v, w+\delta w)$, with $u$, $v$ and $w$ denoted as the displacement components in the directions of $x$, $y$ and $z$ Cartesian coordinate axes. The $x$-axis is set along the direction of the indentation separation, and thus $\delta u = \delta d$, the y-axis lies in the plane of the specimen surface and the z-axis is normal to the specimen surface. Since the incident and reflected laser beams are in the $x-z$ plane, the displacement component $v$ along the $y$-axis should not alter the path length of the laser beams. The method used in holographic and speckle interferometry can be employed to derive the formula of the path length. When $P_1$ moves to $P'_1$, the path length of the laser beam reflected from $P_1$ is changed by the amount of $\delta \Delta_1 = P_1 Q + P_1 Q_2 = u \sin \theta + w(1 + \cos \theta)$, shown in Fig. 3. Similarly, when $P_2$ moves to $P'_2$, the path length of the laser beam reflected from $P_2$ is changed by the amount of $\delta \Delta_2 = (u + \delta d) \sin \theta + (w + \delta w)(1 + \cos \theta)$. Subtraction between $\delta \Delta_1$ and $\delta \Delta_2$ gives the change of the path length difference between beams from the two indentation points as $\delta \Delta = \delta d \sin \theta + \delta w(1 + \cos \theta)$. Therefore, the specimen deformation corresponds to the movement of the interference fringes by

$$\lambda \delta m_1 = (\sin \theta) \delta d + (1 + \cos \theta) \delta w$$

The above equation is derived for fringe pattern 1. In the other reflective direction, the angle between the incident and reflected laser beams takes −θ. As the photo sensors for monitoring the two fringe patterns are mounted opposite to