Two-Color Laser Speckle Shift Strain Measurement System

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ABSTRACT

A two color laser speckle shift strain measurement system based on the technique of Yamaguchi was designed.   The dual wavelength light output from an Argon Ion laser was coupled into two separate single-mode optical fibers (patchcords). The output of the patchcords is incident on the test specimen (here a structural fiber). Strain on the fiber, in one direction, is produced using an Instron 4502. Shifting interference patterns or speckle patterns will be detected at real-time rates using 2 CCD cameras with image processing performed by a hardware correlator. Strain detected in fibers with diameters from 21 microns to 143 microns is expected to be resolved to 15 $\mu\varepsilon$. This system was designed to be compact and robust and does not require surface preparation of the structural fibers.

Keywords: speckle strain, strain measurement, speckle pattern, fiber

1 INTRODUCTION

A nonintrusive strain measurement technique is required due to the small surface area of the fiber test specimens. In the past, extensometers[1] or markers were used for visual observation, but these techniques lack the proper gage length and/or resolution to accurately determine the strain in fibers. A two-color simultaneous strain measurement system has been previously demonstrated[2] based on Yamaguchi's technique.[3] Laser speckles show displacement caused by deformation of a laser illuminated surface. Shifts in speckle patterns are directly related to the strain, translation, and rotation components of the deformation. A non-contact strain measurement system was designed to selectively detect strain in a fiber as it is pulled from one end while the other is held stationary using a driven tensile test machine (Instron 4502).

2 THEORY

The optical geometry of the system is illustrated in Figure 1. The S points mark the center of curvature of the incident laser wavefronts. Object deformation $a(x, y, z)$ of the diffuse surface causes speckle displacements $A[A_X, A_Y]$ at the two observation planes a distance L'_o away from the object plane. Laser positioning lenses (not shown) provide a means of adjusting L_S, the radius of curvature. A far-field diffraction pattern is formed at the observation plane on the assumption that L'_o is much larger than the spot size of the incident beam.
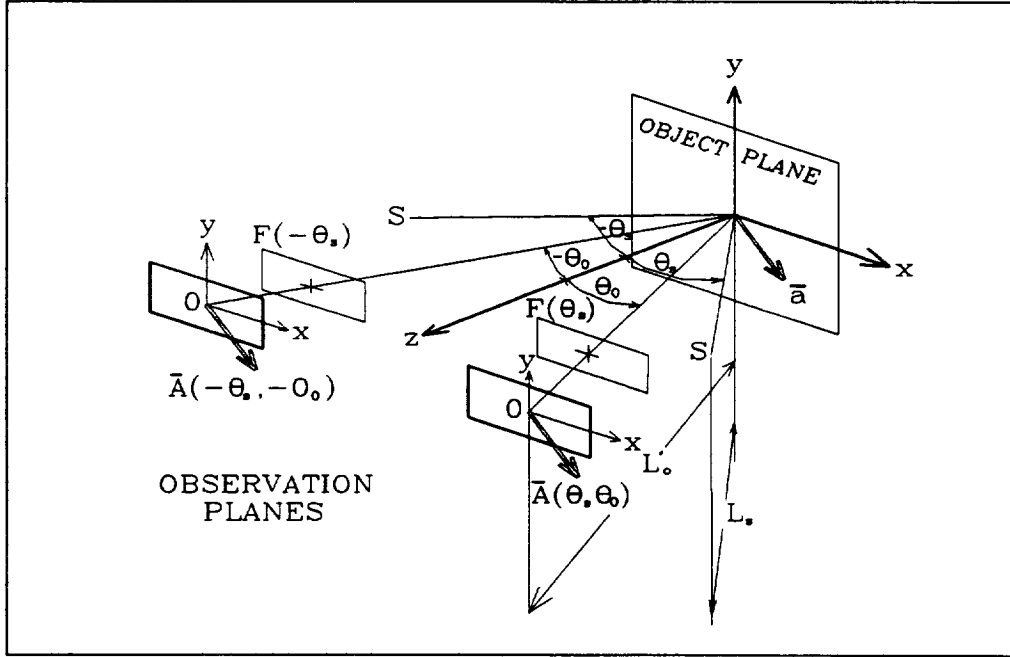

Figure 1: Geometry of optical system.

The speckle displacements are given by[3]

$$
\begin{aligned}
A_X &= -a_x \left[\frac{L'_o}{L_S}(l_{Sx}^2 - 1) + l_x^2 - 1 \right] - a_y \left[\frac{L'_o}{L_S} l_{Sx} l_{Sy} + l_x l_y \right] - a_z \left[\frac{L'_o}{L_S}(l_{Sx} l_{Sz} + l_x l_z) \right] \\
&\quad - L'_o \left[\varepsilon_{xx}(l_{sx} + l_x) + \varepsilon_{xy}(l_{sy} + l_y) + \Omega_z(l_{sy} + l_y) - \Omega_y(l_{sz} + l_z) \right]
\end{aligned}
\tag{1}
$$

where $a_T(a_x, a_y, a_z)$ and $\Omega(\Omega_x, \Omega_y, \Omega_z)$ are the translation and rotation vectors, respectively, and the components of a_T and Ω are the translational and rotational components of rigid body motion, respectively. The unit vectors representing the direction of the center S and the center O are denoted by $l_S(l_{Sx}, l_{Sy}, l_{Sz})$ and $l(l_x, l_y, l_z)$, respectively. The linear x and y components of the strain tensor are designated ε_{xx} and ε_{yy}, respectively, and ε_{xy} is the in-plane shear component.

The two laser sources, at angles of incidence of θ_S and $-\theta_S$ shown in Figure 1, are of different wavelengths (colors). Laser line filters $F(\theta_S)$ and $F(-\theta_S)$ each discriminate against the other source and unwanted background radiation.

2

For the angle of incidence θ_S and observation angle θ_o in the x-z plane,

$$l_s = (\sin\theta_S, 0, \cos\theta_S), \text{ and} \tag{2}$$

$$l = (\sin\theta_o, 0, \cos\theta_o). \tag{3}$$

The X component of $\mathbf{A}(\theta_S, \theta_o)$ is given by

$$A(\theta_S, \theta_o)_X = -a_x \left[\frac{L_o'}{L_S}(\sin\theta_S^2 - 1) + \sin\theta_o^2 - 1 \right] - a_z \left[\frac{L_o'}{L_S}\sin\theta_S\cos\theta_S + \sin\theta_o\cos\theta_o \right]$$
$$-L_o' \left[\varepsilon_{xx}(\sin\theta_S + \sin\theta_o) - \Omega_y(\cos\theta_S + \cos\theta_o) \right]. \tag{4}$$

To eliminate the dependence of the rigid body motion component, the difference between the speckle displacements $A(\theta_S, \theta_o)_X$ and $A(-\theta_S, -\theta_o)_X$ is calculated. That is,

$$\Delta A_X = A(\theta_S, \theta_o)_X - A(-\theta_S, -\theta_o)_X, \tag{5}$$

which after substitution becomes

$$\Delta A_X = -2L_o'\varepsilon_{xx}(\sin\theta_{So} + \sin\theta_o) - 2a_z \left[\frac{L_o'}{L_S}\sin\theta_s\cos\theta_s + \sin\theta_o\cos\theta_o \right], \tag{6}$$

such that

$$\varepsilon_{xx} = -\frac{\Delta A_X}{2L_o'(\sin\theta_S + \sin\theta_o)} \tag{7}$$

when

$$0 = \left[\frac{L_o'}{L_S}\sin\theta_s\cos\theta_s + \sin\theta_o\cos\theta_o \right]. \tag{8}$$

The measurement of linear strain through equation (7) is independent of the rigid body motion components in equation (1) as long as equation (8) is satisfied. This optical constraint can be satisfied experimentally or calculated through knowledge of the laser beam characteristics. From equation (7), the strain in the $\hat{x}$ direction is determined from the differential speckle displacement, speckle shift (ΔA_X), and the geometry of the optical arrangement.

Equation (7) differs from Yamaguchi's ε_{xx} equation by the addition of the $\sin\theta_o$ term in the denominator. Further, in Yamaguchi's case, equation (8) is met by having $\frac{L_o'}{L_S} = 0$, meaning the laser beam waist is incident on the object plane. In the two-color simultaneous system the linear arrays record the speckle patterns at the same time, improving the recording speed by a factor of two over a sequential recording system.

It has been suggested that the linear arrays be placed one above the other rather than the present side by side configuration. For this proposed arrangement, the angle of incidence, θ_S, is still in the x-z plane, but the observation angle θ_o is now in the y-z plane. Thus, $l = (0, \sin\theta_o, \cos\theta_o)$, and

$$A(\theta_S, \theta_o)_X = -a_x \left[\frac{L_o'}{L_S}(\sin\theta_S^2 - 1) - 1 \right] - a_z \left[\frac{L_o'}{L_S}(\sin\theta_s\cos\theta_s) \right]$$
$$-L_o' \left[\varepsilon_{xx}(\sin\theta_S) + \varepsilon_{xy}(\sin\theta_o) + \Omega_z(\sin\theta_o) - \Omega_y(\cos\theta_S + \cos\theta_o) \right]. \tag{9}$$

Substituting equation (9) into equation (5) yields

$$\Delta A_X = -2L_o'\varepsilon_{xx}(\sin\theta_S) - 2a_z \left[\frac{L_o'}{L_S}\sin\theta_S\cos\theta_S \right] - 2L_o'[\varepsilon_{xy}(\sin\theta_o) + \Omega_z(\sin\theta_o)]. \tag{10}$$

3

WAVELENGTH (nm)	PERCENT OF TOTAL POWER
457.9	8%
476.0	12%
488.0	20%
496.5	18%
501.7	5%
514.5	43%

Table 1: Percent of Argon Ion Laser Output Power at Each Wavelength

From equation (10) it is clear that for this configuration, no value of $\frac{L'_a}{L_S}$ can cancel the shear strain and all of the components of rigid body motion.

A correlation algorithm is used to determine ΔA_X. In effect, it overlays the shifted speckle pattern onto the reference pattern and varies the relative positions until the maximum product sum is determined. This maximum corresponds to the speckle displacement between the two patterns. This is represented by

$$R(\Delta X) = \frac{1}{\chi} \int f(X) * g(X + \Delta X) dX, \qquad (11)$$

where $f(X)$ is the reference speckle pattern, $g(X + \Delta X)$ is the shifted speckle pattern and ΔX is the amount of the shift. The integral is computed repeatedly for increasing values of ΔX. The value of ΔX for which R is a maximum is the amount of shift in A_X between the before-strain and after-strain speckle patterns.

This correlation is performed between the reference and shifted patterns from the θ_s incident beam, and then again for patterns from the $-\theta_s$ incident beam. The difference between the values of A_X is then used in strain equation (7) to calculate the surface strain.

3 EXPERIMENTAL SETUP

3.1 Optics

A schematic of the optical system used to couple the output of an Argon Ion laser (operating in multi-line mode) into two single-mode fibers is shown in Figure 2. The coupling optics are mounted on a small optical bench which is then mounted vertically in a test cabinet. The outputs from the optical fibers are inserted into the sensor head having the geometry previously shown in Figure 1.

As illustrated in Figure 2, the laser light output is reflected off a mirror onto a dispersion prism which separates the beam into its component wavelengths. This light is reflected off the two mirrors and coupled into two single-mode fibers. The power spectrum of the laser is given in Table 1, showing that the logical choice for specimen illumination colors are blue and green, 488 nm and 514.5 nm. An attenuator is placed in front of the green fiber coupler to reduce its intensity so that the blue and green have identical power. To eliminate undesired wavelengths coupling into each of the optical fibers, a slit is placed directly in front of each.

The outputs of the optical fibers are connected to the sensor head assembly, several feet from the
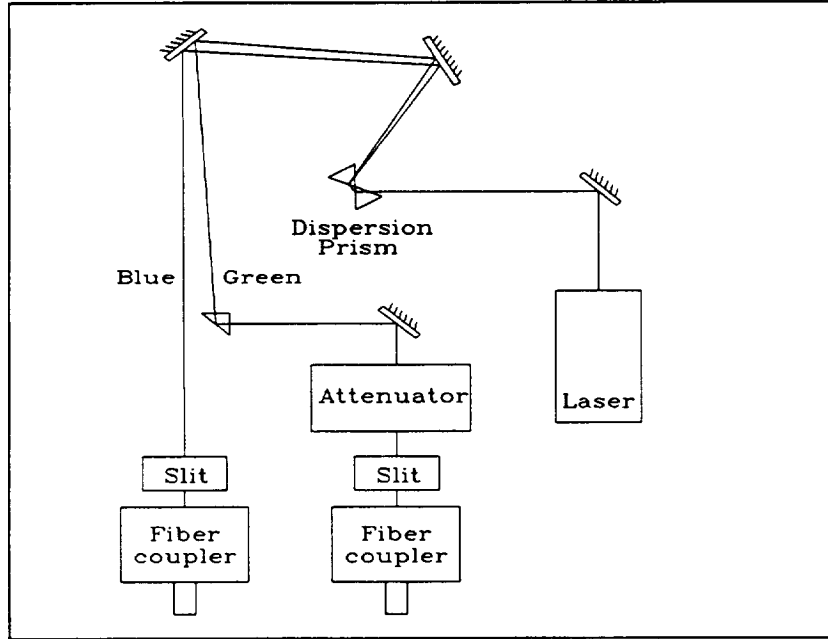
Figure 2: Optics coupling laser light into two single-mode fibers.

coupling optics. This assembly consists of a collimator and focusing lens and was designed for the beam waist to be incident on the fiber being strained. Approximately 1 W of collimated laser power must be coupled out of the optical fibers to illuminate the specimen.

The two colors are incident on the test fiber at an angle of $\theta_S = 30°$. Light reflected off the fiber being strained travels to two CCD array detectors, each with an optical filter to block unwanted wavelengths (See Figure 1). Because two CCD's are required, there is an angle (θ_o) between the sample normal and each detector.

3.2 Electronics

A block diagram of the system setup is shown in Figure 3. The speckle pattern is detected by two linear CCD array boards controlled by the real-time hardware correlator. The correlator assembly is comprised of a control board and two correlator slice boards. The control board also interfaces to the IBM PC and stores data frames, initiates correlator sequences, and selects which stored frames will be used for the reference fields. Two correlator slice boards calculate the correlation for each CCD array. The resulting speckle displacements observed by each CCD array are converted to analog signals which are simultaneously digitized with the analog load and extension signals from the Instron. The control functions of the Instron are interfaced to the IBM PC via a GPIB card.

The data is hard-limited[4] to take advantage of the massive parallelism of an architecture based on fuzzy pattern comparator ICs[5].[6] Hard-limiting is achieved when a field of data from the CCD array is compared to the mean of the previous field. Data values equal to or greater than the mean are
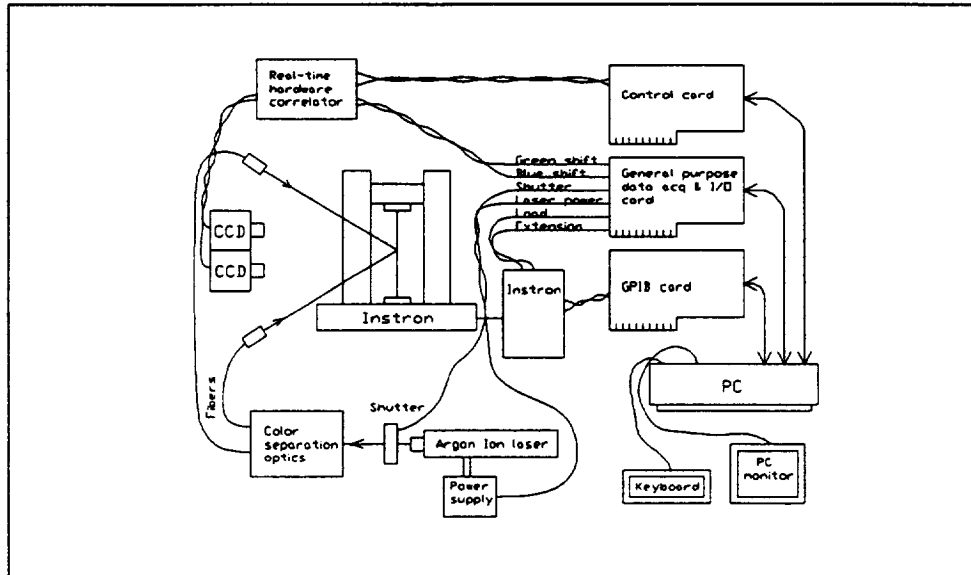
Figure 3: Block diagram of electronics.

assigned a value of one, otherwise a value of zero is assigned. While this comparison is taking place, the hardware is simultaneously calculating the mean for the next data set comparison. Given 8 fuzzy comparator ICs with 8 accumulators each, 64 bins of the correlator function are calculated as the Hamming distance between the incoming data set and a reference at each of the 64 displacements. The minimum of the Hamming function asymptotically approaches the maximum of the correlator function given in equation (11). The output of the correlator yields the speckle displacement, A_χ. Calculating the difference in the displacement between the two beams provides the speckle shift, ΔA_χ. From this, the strain can be directly calculated using equation (7).

4 RESULTS

Using data acquired from a previous system setup,[7] it was shown that the minimum of the Hamming function asymptotically approached the maximum of the correlator function. This validated our choice of algorithm and hardware architecture. Furthermore, random data processed through hardware consisting of a fuzzy pattern comparator and the mean value calculating hard-limiting circuits produced the output shown in Figure 4. Here, the minimum corresponds to unshifted 1-bit data sets, which is analogous to the maximum for $\Delta X = 0$ in equation (11).
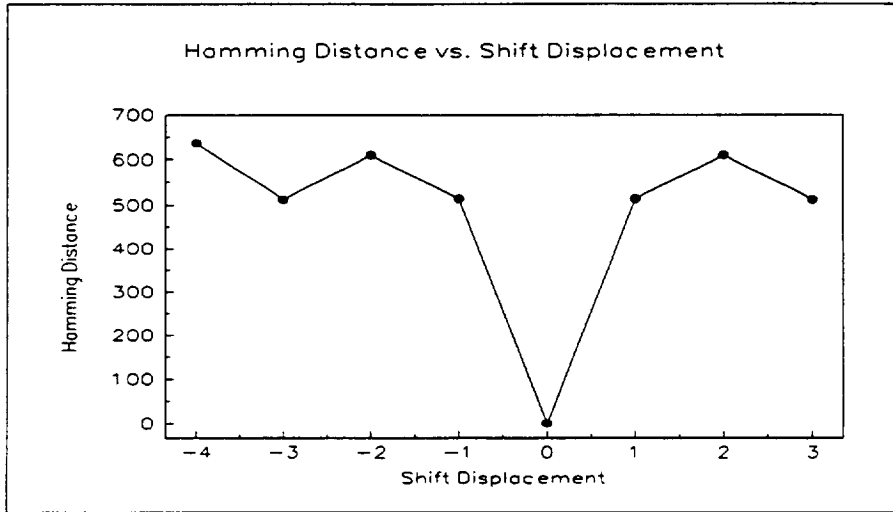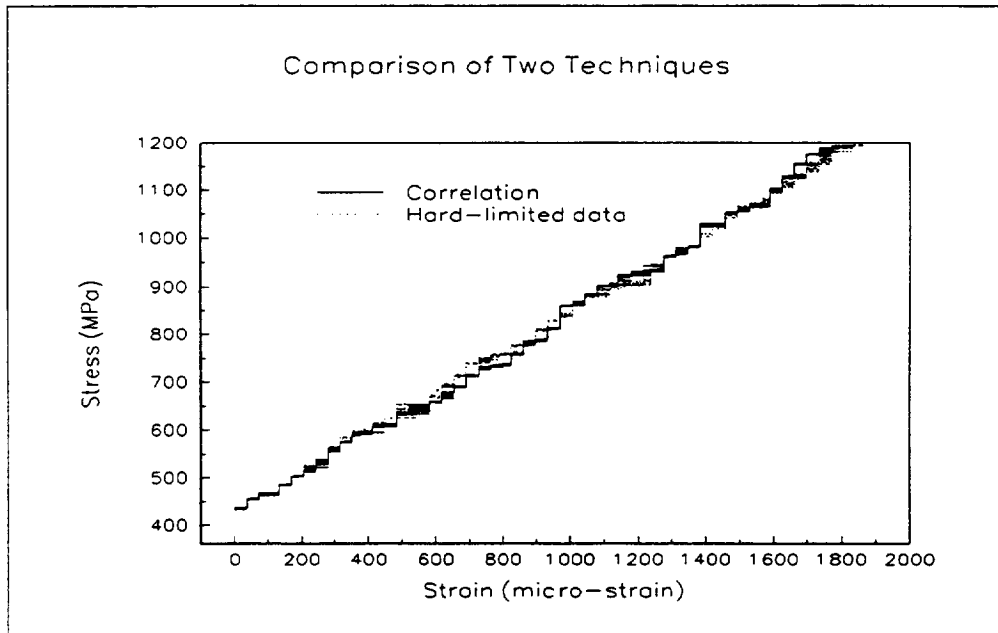
Figure 4: Hamming distance vs. shift displacement

Comparison of two techniques.

Figure 5 compares actual stress vs. strain data from the original speckle rig[8] which used equation (11) on 8-bit speckle data to the same data hard-limited and processed by the Hamming distance algo-

rithm. Results shown agreed, indicating that the algorithm chosen can be suitably substituted for the correlator-based system. Using the traditional correlator algorithm requires a great deal of computational overhead which results in a time and/or hardware penalty. The 1-bit Hamming algorithm uses smaller data paths, less computational intensity, and allows for the use of commercial off the shelf ICs. Thus, this method efficiently processes the data to exceed the real-time control rate of the Instron, thereby allowing for off-line characterization of samples.

5 SUMMARY

A two-color speckle strain system has been designed. The optics have been completed and tested. Proof of concept electronics have been tested and a system designed to achieve real-time data rates. In the future, an oven will be placed around the fiber mount of the Instron such that strain measurements can be taken at temperatures exceeding $1000^\circ C$ degrees.

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