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# Advanced One-Dimensional Optical Strain Measurement System – Phase IV

Christian T. Lant
*Sverdrup Technology, Inc.*
*Lewis Research Center Group*
*Brook Park, Ohio*

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Christian T. Lant
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

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# Advanced One-Dimensional Optical Strain Measurement System - Phase IV

Christian T. Lant
Sverdrup Technology, Inc.
NASA Lewis Research Center Group
Brook Park, Ohio 44142

## SUMMARY

The Instrumentation and Control Technology Division at NASA Lewis Research Center has developed a high performance optical strain measurement system for high temperature applications using wires and fibers. The system uses Yamaguchi's two-beam speckle-shift strain measurement technique, and automatically calculates accurate surface strains at a rate of 5 Hz using a digital signal processor in a personal computer. The system is fully automated, and can be operated remotely.

This report describes the designs and methods used by the system, and shows low temperature strain test results obtained from small diameter tungsten, silicon carbide, and sapphire specimens. These specimens were chosen due to their roles in composite materials research.

## INTRODUCTION

The NASA Lewis Research Center has been engaged in an ongoing effort to develop a non-contacting optical strain measurement system. This measurement system is intended for use on test specimens subject to hostile environments, such as those found in earth-to-orbit propulsion systems.

This effort has developed strain measurement systems that can measure strains along one or two principal axes at a point on a flat test specimen, at high specimen temperatures. Uniaxial strains have been measured beyond 750°C, and two principal strains have been measured at 650 °C.[1-2] The systems are based on the laser speckle-shift strain measurement technique of Yamaguchi,[3] which utilizes the linear relationship between surface strain and laser speckle shifts in the Fraunhofer diffraction plane. This technique accurately measures surface strains in the presence of rigid body motions of the specimen, and requires no surface preparation. The optical system is very stable and requires no periodic adjustment, once initially aligned.

A feasibility study investigated theoretical aspects of using the system on small diameter wires and fibers at high temperatures.[4] Interest in fiber and wire materials research for the development of high temperature composites has led to the current focus of this effort, which is to make real-time one-dimensional strain measurements.

The current effort advances the state-of-the-art of Lewis' optical strain measurement system, and demonstrates the successful application of the speckle-shift technique to small diameter wire and fiber specimens. Although the system is certainly not restricted to making measurements on wires and fibers, the testing emphasized these specimens to demonstrate measurements on a traditionally difficult application. In the past, strain measurements on these specimens have been made using extensometers, or even visual observation of the movement of flags on the specimen surface. These techniques have suffered from either a long gage length and/or low strain resolution. The optical technique described here features a short gage length (< 1 mm) and a strain resolution of about 15 $\mu\varepsilon$. It requires no surface preparation, and can make measurements at very high temperatures. It is estimated that measurements are feasible on specimens as hot as 2000 °C, under controlled conditions.

The improvements added to the current system address limitations of the previous systems. In particular, the low strain measurement rate of the previous speckle-shift systems, on the order of 0.1 Hz, limited the response time of the tests. The previous systems were limited to making strain measurements under strictly static conditions. Higher sampling rates and, therefore, higher computation rates were desired to allow continuous loading of the specimen at higher strain rates. This report describes a system designed to provide high performance at low cost. The system has achieved a performance increase of nearly two orders of magnitude over the previous system, using modular, off-the-shelf components at a relatively low price.

A high speed image processing system has been assembled to perform the strain calculations with near-real-time results. The use of a two-dimensional charge-coupled device (CCD) for the detector provides the flexibility of a standard video interface, and reduces decorrelation errors due to rigid body motions when using a two-dimensional specimen. This system is often called the "concurrent processing" system, referring to the fact that it reduces the speckle data concurrently with the acquisition during the test, instead of storing the data for later processing. This document describes the test equipment and results obtained from this laboratory system.

**Theory**

Objective laser speckle patterns, generated by spatially coherent illumination of a rough specimen surface, shift when the surface is strained or when the specimen undergoes rigid body motion. The speckle patterns are recorded on a sensor array, and cross-correlations of the patterns before and after they move are calculated to determine the amount of shift between them (the peak position of the cross-correlation indicates the number of picture elements (pixels) the particular speckle pattern moved). Figure 1 is a schematic of the optical setup. The figure shows a dual beam configuration, which allows automatic cancellation of rigid body motion. By taking the difference in shifts of the speckle patterns generated independently by two laser beams incident on the specimen from equal but opposite angles, error terms due to rigid body motion are canceled.

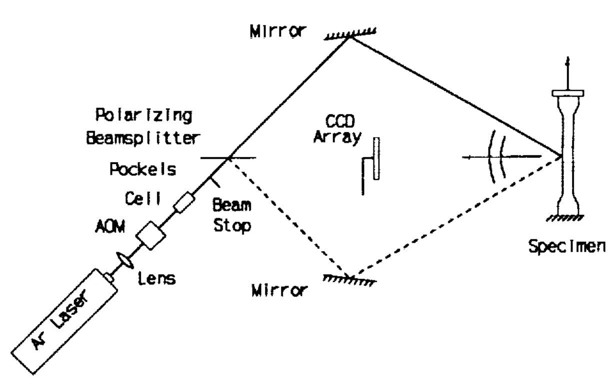


**Figure 1:** *Optical schematic*

The geometry of the optical setup and careful alignment of the specimen limit strain-induced speckle shifts to an axis parallel to the sensitive axis of the measurement system, namely, the incident plane of the laser beams. Off-axis shifts due to rigid body motion, however, are not suppressed by this technique.

Previously, when a linear photodiode array was used, the speckle patterns remained correlated as long as they did not shift along the transverse direction, off the sensor array.

The current system measures one-dimensional strain in near-real-time on small diameter wires and fibers, as well as extended flat specimens, by using a digital signal processor (DSP) for the calculation intensive cross-correlations. Rigid body motion constraints and decorrelations are reduced by using a two-dimensional CCD array to record an extended speckle pattern. A two-dimensional extended pattern allows off-axis speckle shifts to be tracked dynamically, without irrecoverable decorrelation.

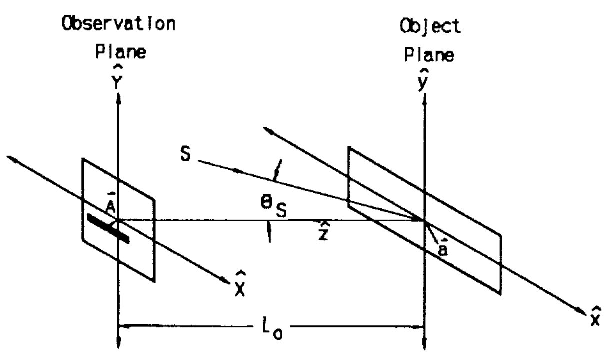


**Figure 2:** *Simplified coordinate system*

Figure 2 shows the simplified geometry of the coordinate system. The specimen is in the x,y plane, and the sensor is defined to lie in the X,Y plane. The x,y and X,Y planes are separated by a distance $L_0$ along the z axis. Deformation of object points on the specimen surface are described by vector a(x,y), and the resulting shifts of the speckle pattern are given by vector A(X,Y). The shaded rectangle in the figure indicates a one-dimensional reference slice of the speckle pattern (one line of the 2-D CCD array) shifted from the origin by A(X,Y). The x,z plane is the plane of the incident laser beam, which comes from source point S.

After rigid body motion terms are canceled out of the simplified speckle-shift equations, the surface strain $\varepsilon_{xx}$ in the x direction can be calculated by the relation

$$\varepsilon_{xx}=\frac{-\Delta A_X}{2L_o\sin(\theta)} \qquad (1)$$

where the incident angle $\theta = |\theta_S|$, and $\Delta A_X$ is the difference between speckle shifts from the two beams

$$\Delta A_X=A_X(\theta_S)-A_X(-\theta_S). \qquad (2)$$

Typical values for the constants in Equation 1 are given in Table I. $L_S$ is the radius of curvature of the incident laser beam.

**Table I**

| Constants | |
|---|---|
| $L_o$ | 0.577 m |
| $L_S$ | >100 m |
| $\theta$ | 30° |

## SYSTEM REQUIREMENTS

In this effort we developed a one-dimensional strain measurement system capable of calculating strains in near-real-time (~5 Hz). A high speed DSP (TI's TMS320C30) supplemented the computer, in order to achieve this performance. The system provides the ability to continuously track on-axis and off-axis speckle movements from a stressed specimen, and thereby measure the instantaneous strain on demand. The system is always up-to-date on the current speckle shifts, because the tracking is automatic and continuous. Continuously tracking the shifts in small increments reduces the range requirements of the correlation, which speeds up the tracking process. In addition, the ability to continually track the speckle patterns when off-axis speckle movements occur diminishes decorrelation errors due to secondary correlation peaks and, therefore, increases the measurement range of the instrument. Secondary correlation peaks, which can become prominent in the event of partial decorrelation, are not observed because the required shift range of the correlation is small. In addition, the alignment criteria for the test specimen are not as stringent because the system is more tolerant of larger rigid body motions, and less specialized load apparatus can be used for the tests.

Full field speckle patterns are recorded electronically by the system as the specimen undergoes strain and rigid body motions. When a speckle pattern shifts off the primary viewing axis (i.e. perpendicular to the incident plane) during a run, the reference slice (the central line of the unshifted speckle pattern) will still be somewhere on the two-dimensional sensor array and correlation can be maintained. Note, however, that this is a much more important feature for testing bar specimens than for testing very narrow specimens. Tests showed that for quasi-one-dimensional specimens (defined roughly as specimens much narrower than the laser spot diameter), such as wires or fibers, the correlations are relatively insensitive to transverse speckle shifts. This point will be discussed in more detail in the section on results.

It is necessary to perform at least four correlations per strain point to track the speckle shifts in two dimensions - one for each beam, along two axes. When performing a 2-D correlation, therefore, the processing demands of the longer calculation make the system exceedingly slow unless a high speed processor is used. Indeed, even a 1-D correlation limits the response of the system if the correlation cannot be performed at a rate near the data acquisition rate. In addition to finding the coordinates of the correlation peak, the DSP-based image processor in this system automatically updates the reference patterns before decorrelation occurs. This allows a virtually unlimited range for tracking strain and rigid body motion shifts, with relatively small accumulated decorrelation errors.

## SYSTEM DESIGN

### Hardware

The optical system uses a switched single beam design, for compactness, following the schematic in Figure 1. The argon ion laser beam is diverted into the beam stop by the acousto-optic modulator (AOM) between tests and exposures. The Pockels cell and polarizing beamsplitter form an optical switch, in order to provide two beam paths for the error cancellation. The Pockels cell rotates the polarization of the beam by $\pi/2$ radians on demand; this allows the beam to either pass through the polarizing beamsplitter, or be reflected to the other beam leg. A waist positioning achromatic lens provides a planar wavefront at the specimen surface, in order to maximize error cancellation.[2,3]

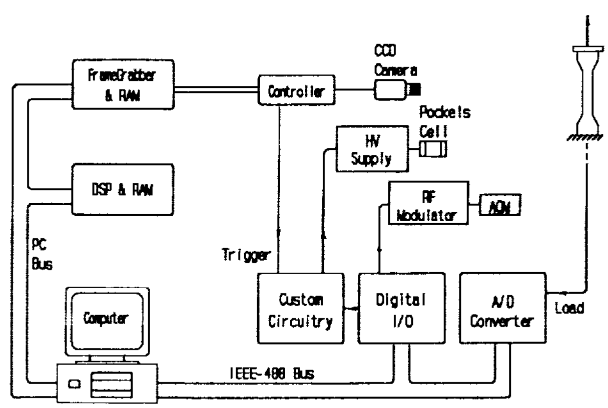


Figure 3: *Block diagram of system*

The data acquisition system is based on a high performance personal computer (Intel 80486 CPU), with a VGA graphics adapter using a graphics co-processor. This PC is the system controller, synchronizing the video and load data acquisition with the strain calculations. Figure 3 shows a block representation of the system control paths. The image processing system components, which perform the strain calculations, plug into the computer's 16-bit I/O bus (PC bus). The computer executes custom programs, optimized to perform various overhead operations, while the image processor acquires the speckle image data from the CCD camera controller and correlates the images. A simple, custom digital circuit switches the Pockels cell in synchronization with the camera. This synchronization circuit is basically a flip-flop, driven by the RS-170 even/odd field signal supplied by the CCD camera circuitry (labeled "trigger"). The exposures for the two beams are timed for successive video frames, 1/30 second apart. The output of the custom circuit is a line driver that toggles the state of the Pockels cell. The computer has an IEEE-488 bus (GPIB), to which is connected a digital I/O unit, and an analog-to-digital converter (A/D converter). The digital I/O unit controls the state of the acousto-optic modulator by turning on or off the RF signal to the crystal. The A/D converter digitizes the voltage across a load cell connected to the specimen mount.

The fibers and wires are mounted in a custom load rig. The load cell is connected to the fixed specimen grip in the rig. A stepping motor with a fine pitch lead screw moves the other grip along rails, applying a load to the specimen. The resolution of the stepping motor is much finer than the resolution of the load cell, so the loading is essentially continuous.

### Software

The software for the system is written in the C programming language. This language provides the features of flexibility, speed, and compatibility with the third-party development libraries used to integrate the system. The software is divided into two distinct programs: one program executes on the DSP, and the other runs on the system computer.

The code residing on the DSP performs the correlations necessary to track the speckle shifts. The DSP sends the computer a continual stream of speckle shift values. The main program, which resides on the computer, initializes the on-line hardware components, transfers image data between the frame grabber and the DSP board, and provides the operator interface for controlling the system. The computer interprets the shift data from the DSP, and creates an array of stress/strain values for the test run. The time and temperature can also be stored for each stress/strain point. The processed data is stored on magnetic media after the test run is completed.

Graphical windows give the operator up-to-date information on the tracking system as the run progresses. The functions available to the operator are selected from pop-up menus. The graphics co-processor takes much overhead off the system computer's CPU.

Each algorithm within the data acquisition loop is optimized to decrease the system overhead as much as reasonably possible. A stress/strain point can be measured in 200 - 300 milliseconds, depending on the filter length (number of pixels used to represent the reference speckle pattern) used for the cross-correlation. Most of this time is spent transferring speckle data from the frame grabber to the DSP, and updating the graphics displays on the computer. The graphics displays can be disabled for even faster operation.

## PROCEDURES AND RESULTS

### Test Procedures

Tests of the system demonstrated the performance of the concurrent processing speckle tracking technique, and its effectiveness in reducing test equipment specifications, required in previous systems solely to meet the needs of the sensor. Tests induced rigid body motion to determine the 2-D array's effectiveness in maintaining correlation in the event of off-axis speckle shifts, and translations of the gage location away from the laser spot. In addition, optically measured strain values are plotted against load to show if unexpected systematic and/or random errors affected the measurements. Although past testing fully verified the accuracy of the speckle-shift technique in measuring strain on flat specimens, it was necessary to check the ability of this version of the system to separate strain from error terms using synchronized data acquisition on small diameter wires and fibers.

Specimens were independently rotated and translated, while under no induced strain, in order to separate the responses of these rigid body motions. Pure specimen rotations shifted the speckle patterns in the X,Y plane, which allowed detection of apparent strain due to tracking errors. Pure in-plane specimen translations tested the ability of the image processor to maintain accurate tracking while the gage position moved, and the speckle patterns changed and decorrelated. Finally, measuring the linearity of strain versus applied load tested the system under its normal mode of operation.

## Results

Tests inducing pure rigid body motion indicated that cancellation was within the resolution of the system for the most sensitive rigid body motion terms in the $A_X$ component of shift. Since $A_X$ is the displacement component containing the strain term, this is where error cancellation is important. Tests were conducted using a flat bar Inconel 600 specimen for maximum signal, so signal-to-noise considerations would not be a factor in the test.

The cancellations were measured for $a_x$, $a_z$, $\Omega_y$, and $\Omega_z$ (two translation components and two rotation components), which include the components most likely to lead to error in $A_X$. The rigid body motions were induced at a rate slow enough to be followed by the system, i.e. no movements during each measurement period were of magnitude larger than the search region of the correlations. In addition, cancellations were observed when the state of the specimen was static, to ensure that both beams were measuring the same position of the specimen.

The sensitivity of the system to off-axis speckle shifts ($A_Y$) depends greatly on the specimen geometry. In accordance with

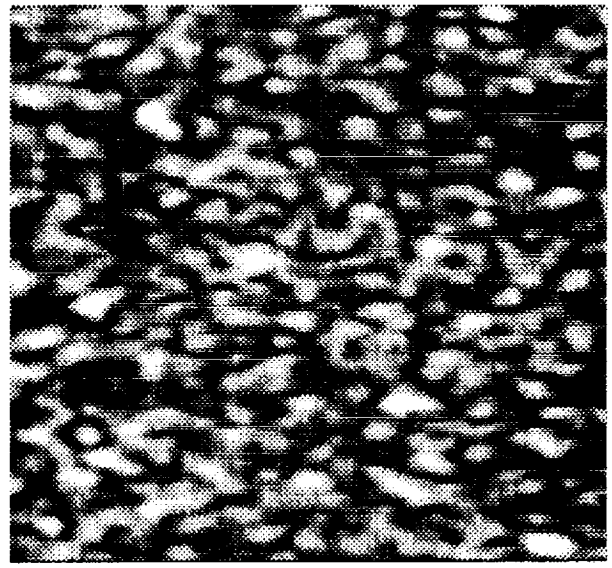

**Figure 4**: *Speckle pattern from a slightly elliptical spot*

diffraction theory, the speckle pattern characteristics depend on the shape and size of the laser spot on the specimen. The cross-section of the laser spot on a flat specimen is slightly

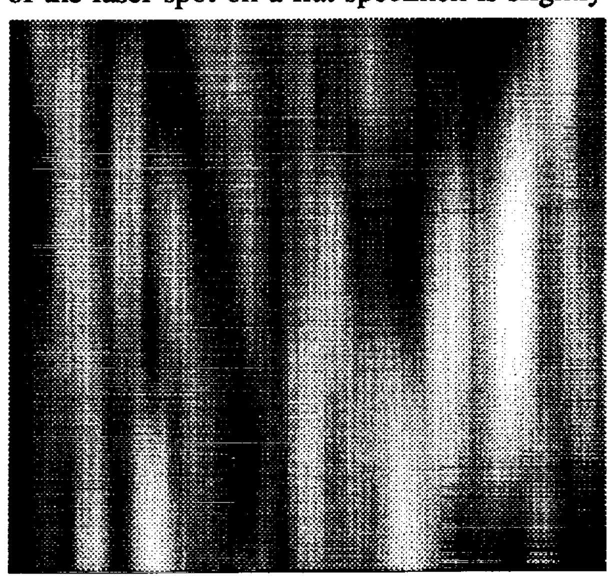

**Figure 5**: *Speckle pattern from a highly elliptical spot*

elliptical, due to the angle of incidence $\theta_S$ of the laser beam. The resulting speckle pattern, as shown in Figure 4, has a distribution of fairly symmetrical speckles. However, in the case of a very small diameter cylindrical specimen (much smaller than the spot diameter), such as a fiber or wire, the illumination cross-section of the laser spot is truncated and the resulting speckles are highly elongated in the direction perpendicular to the long axis of the specimen. An example of this type of speckle pattern is shown in figure 5. Tests showed that the correlations were relatively insensitive to transverse speckle movements (vertical movements in the plane of the figure) for this type of speckle pattern. This result might be expected by observing that the speckle intensities vary slowly in the vertical direction, compared to the strain-sensitive horizontal direction.

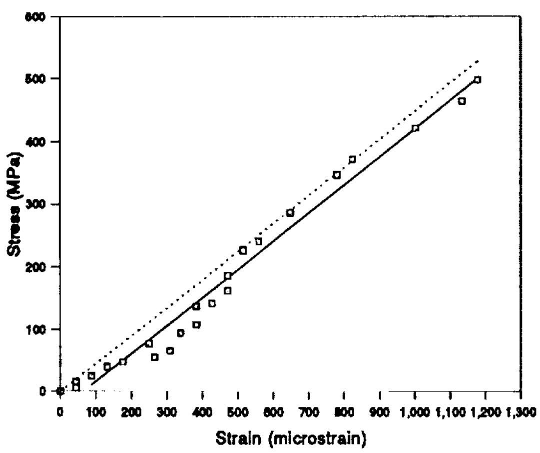


**Figure 6**: *Stress-strain plot for 150 μm diameter Saphikon, at room temperature*

This situation has both advantages and disadvantages. A disadvantage is that the average light level at the detector is lowered, reducing the signal-to-noise ratio. This is especially significant when measuring strain on ceramic specimens, which characteristically give lower speckle visibility to begin with. One advantage, however, is that it is not necessary to track speckle movement in the transverse direction, since decorrelation due to these shifts occurs much slower. As a result, the lower system overhead allows the strain measurement rate to increase.

Figure 6 shows a plot of stress versus strain for a 150 μm (6 mil) diameter sapphire fiber (Saphikon). The solid line indicates a least-

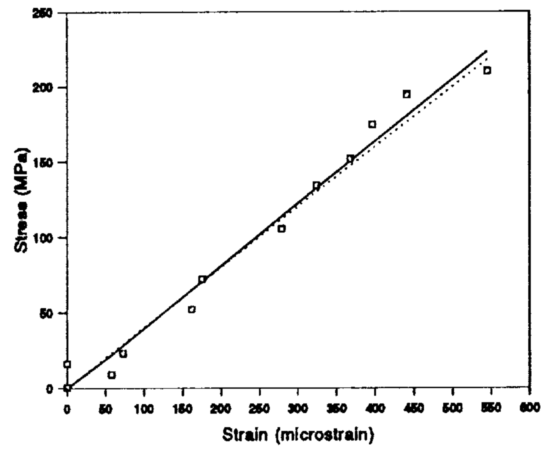


**Figure 7**: *Stress-strain plot for 140 μm diameter SiC fiber, at room temperature*

squares linear regression of the data. The dashed line indicates the theoretical stress-strain data whose slope represents the published value of Young's modulus for this material. The measured modulus is 450 GPa (65 Msi), which agrees with the handbook value of modulus to within two significant

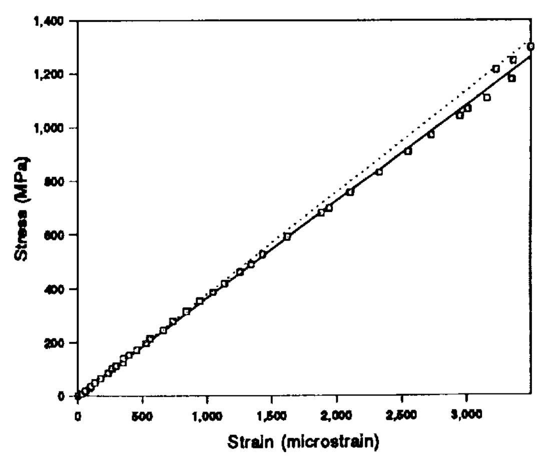


**Figure 8**: *Stress-strain plot for 76 μm diameter W-3% Re wire, at room temperature*

figures. The RMS deviation of the strain points from the fit is 50 με. The correlation coefficient of the linear fit is 0.99.

Similarly, figure 7 shows a stress-strain plot of a 140 μm diameter silicon carbide fiber (Textron SCS-6). The measured modulus is

410 GPa (60 Msi) and the handbook value is 400 GPa (58 Msi). The RMS deviation of the strain from the fit is 25 $\mu\varepsilon$. The correlation coefficient of the fit is 0.99.

Figure 8 shows a plot of the stress-strain values measured on a 76 μm (3.0 mil) diameter tungsten-3% rhenium wire specimen. The value of Young's modulus given by a fit of the measured data is 360 GPa (52 Msi) and the handbook value is 380 GPa (55 Msi). The discontinuity in the data at 1200 MPa was caused by a false correlation, such as discussed in the error analysis section, which offset the subsequent strain values by about 170 $\mu\varepsilon$. The RMS deviation of the corrected strain data from the fit is about 22 $\mu\varepsilon$. The correlation coefficient of the fit is 1.0.

### Error Analysis

The optical configuration is basically a single axis version of the Phase II optical system.[2] As such, the systematic errors come from the geometrical uncertainties in the optical setup, as described previously.[1] Fundamentally, it is possible for the accuracy of the strains measured by this system to be within the theoretical accuracy (≈within 1 pixel shift) if three criteria are met:

- Rigid body motion shifts must cancel.
- The specimen must be stationary for the time required to record a speckle pattern from each beam (two consecutive frames).
- The cross-correlations must peak within one pixel of the actual speckle shift.

Deviations from these criteria can cause errors that are significant, although measurements can still be made.

The first criterion, as distinct from the second, requires the geometry of the optical system to be within some tolerance, such that approximations in the speckle shift equations are valid. For example, the sensor is required to reside in the incident plane of the laser beams, so that the z-component of specimen rotation does not induce a speckle shift. The references[1,3] discuss the shift equations in greater detail; the discussion here is on their significance as an error source. Other terms of rigid body motion are eliminated from the strain equation by requiring a very large radius of curvature, $L_S$ (the effective distance between the source point and the gage location), of the laser beam at the specimen surface. Refer to Table I for the value of $L_S$. Each rigid body motion error term has at least one system parameter, or approximation, that must be set accurately to ensure complete cancellation. The measurements of rigid body motion cancellation given in the results section experimentally verified that these approximations were valid.

The remaining rigid body motion terms are not intended to be canceled by these approximations, and are symmetric, with respect to the incident angle, in that they induce speckle shift in the same direction along the X axis for each beam. The second criterion, above, refers to the assumption of simultaneity of shifts for each beam (the errors cannot be fully canceled if the two beams are not measuring the same state of the specimen). As shown in equation 2, the remaining rigid body motion shifts are canceled by subtracting the total shift of the speckle patterns from each beam. This cancels the symmetric, or even, terms (rigid body motion errors) and adds the asymmetric, or odd, term (strain).

Observations show that large random errors occur when the specimen movements are too fast. The correlation peak indicating the speckle displacement may actually be a secondary peak. This secondary peak is likely to be one speckle diameter away from the actual peak, leading to an error of hundreds of microstrain. Large amplitude vibrations of the specimens also increased the scatter in some of the strain data. Vibrational frequencies greater than the order of the camera frame rate would cause small differential speckle shifts between the two beams, leading to additional strain errors typically observed to be around 30 $\mu\varepsilon$. Wires and fibers are more prone to vibrate than more rigid specimens, so this point should be addressed when choosing the test environment.

The third criterion refers to the statistical accuracy of the cross-correlation technique for any particular sampling of a speckle pattern. In order for the cross-correlation to accurately determine the speckle pattern shift, assuming the patterns are correlated in the first place, the finite sample being correlated must possess the same statistics (e.g. mean, distribution) as the full speckle pattern on the whole. Otherwise, the correlation values depend on which particular subregion of the speckle pattern is being sampled.

Stated in statistical terms, a process whose statistics are independent of origin is said to be *stationary*. If, further, the ensemble average statistics of a process can be computed from a single spatial record, the process is also said to be *ergodic*. However, if the samplings of the speckle patterns are small enough, then they will not possess the statistics of the process on the whole. Correlation errors have indeed been observed when using smaller speckle pattern samples. For example, an unusually bright region at the edge of the sampled pattern could alter the shape and location of the correlation peak, causing an error in the measured shift and, therefore, an error in the measured strain.

Tests of the correlation algorithm showed that as the correlation filter length was increased from 25 to 400 pixels, by factors of two,

1) the visibility of the autocorrelation curve varied less for different sets of data,

2) the cross-correlation curves became more similar for different sets of data, and

3) the accuracy of the correlations improved.

These tests suggested that the sample length of the speckle patterns used in the correlations should be greater than 200 pixels for them to have the statistics of the speckle pattern on the whole, for the particular speckle sizes generated by the current optical configuration. Although speckle patterns can be considered ergodic processes, the sample must represent this for the correlation technique to be reliable.

Other factors in the accuracy of the correlation include the exposure level of the CCD array (SNR), and fixed pattern noise in the camera. Statistical uncertainties in the correlations from the image processing system (resolution limits and cumulative error) should be similar to those encountered in previous systems.

The theoretical resolution limit of the system is calculated to be 15 $\mu\varepsilon$, for a shift of one pixel. This leads to an RMS expected error of about 4 $\mu\varepsilon$. The observed RMS deviation of the strain measurements from the measured trends ranged from 22 to 50 $\mu\varepsilon$. It is believed that the observed errors are due in part to specimen vibrations (incomplete rigid body motion cancellation) and correlation errors caused by camera fixed pattern noise, and in part to a combination of partial decorrelation, and limited correlation filter length.

What is called "fixed pattern noise" here is actually an imbalance of the three amplifiers in the camera controller. The noise is unusual in that the fixed pattern signal level is proportional to the speckle intensity at the individual pixels. Therefore, it cannot simply be subtracted from the speckle exposures. The fixed pattern noise was balanced as much as allowed by the trim potentiometers in the camera controller. The remaining signal decreased the resolution of the system slightly, by imparting a low amplitude modulation on the correlation curve at the spatial frequency of the fixed pattern. Vibration errors were reduced significantly by isolating the specimen from air currents and floor vibrations.

It is important to note that this vibration sensitivity is distinct from that of interferometric measurement techniques. Interferometric techniques fail completely for even small amplitude vibrations (~0.5 μm), whereas this technique is only sensitive to relatively large differential movements during the acquisition of each speckle pattern pair. For example, a 10 μm differential specimen translation only gives a position error of one pixel. Correlation, however, can be maintained for a translation of roughly half the laser spot diameter (~0.5 mm).

The correlation filter length was increased to 200 pixels for the tests shown in the results. The maximum practical filter length for the CCD array used in the tests is about 470 pixels, which could further improve the correlation statistics.

## CONCLUSIONS

There are two critical changes implemented in the speckle-shift strain measurement technique that, combined, create a speckle tracking system that greatly increases the usefulness of the technique. A two-dimensional CCD array camera prevents off-axis speckle shifts from causing excessive decorrelation, when using bar-type specimens, and a DSP-based processing system allows strain to be calculated at a rate near the data acquisition rate. Care should be taken to use a characteristic sampling of the speckle pattern in the correlation filter, to reduce correlation errors.

Recommendations for future work include the following elements:

- Record simultaneous speckle patterns for each beam;
- Reduce the speckle data transfer time required to perform the correlations;
- Reduce the size of the optical head to facilitate measurements in a test cell;
- Refine the algorithm used to track transverse speckle shifts;
- Demonstrate feasibility of a four-beam two-dimensional strain measurement technique.[5]

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# REPORT DOCUMENTATION PAGE

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Lewis Research Center Group
2001 Aerospace Parkway
Brook Park, Ohio 44142

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**13. ABSTRACT *(Maximum 200 words)***

An improved version of the speckle-shift strain measurement system has been developed. The system uses a two-dimensional sensor array to maintain speckle correlation in the presence of large off-axis rigid body motions. A digital signal processor (DSP) is used to calculate strains at a rate near the RS-170 camera frame rate. Strain measurements have been demonstrated on small diameter wires and fibers used in composite materials research. Accurate values of Young's modulus have been measured on tungsten wires, and silicon carbide and sapphire fibers. This optical technique has measured surface strains at specimen temperatures above 750 degrees Celsius, and has shown the potential for measurements at much higher temperatures.

**14. SUBJECT TERMS**

Laser speckle; High temperature strain measurement; Optical strain measurement; Wire and fiber; Speckle correlation

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