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Compact Simultaneous-Beam Optical Strain Measurement System

Phase V

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SUMMARY

Recent advances on the laser speckle strain measurement system under development at NASA Lewis Research Center have resulted in a compact, easy-to-use measurement package having many performance improvements over previous systems. NASA has developed this high performance optical strain measurement system for high temperature material testing applications. The system is based on I. Yamaguchi's two-beam speckle-shift strain measurement theory, and uses a new optical design that allows simultaneous recording of laser speckle patterns. This design greatly improves system response over previous implementations of the two-beam speckle-shift technique. The degree of immunity to transient rigid body motions is no longer dependent on the data transfer rate. The system automatically calculates surface strains at a frequency of about 5 Hz using a high speed digital signal processor in a personal computer. This 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-rhenium and palladium-chrome wires.

INTRODUCTION

Strong, lightweight structural materials being developed for high temperature aeronautical and astronautical applications have pushed test measurement requirements beyond traditional measurement techniques. The Instrumentation and Control Technology Division at NASA Lewis Research Center has been engaged in an ongoing in-house effort to develop non-contacting optical strain measurement systems for high temperature material testing applications.

This effort has developed strain measurement systems that can measure strains along one or two principal axes at a point on a 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 two-beam laser speckle-shift strain measurement technique of Yamaguchi,[3] which uses the linear relationship between surface strain and laser speckle shifts in the Fraunhofer diffraction plane. This non-contacting technique can accurately measure 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. The speckle-shift optical technique described in the theory section also features a short gage length (<1mm) and a strain resolution of about $15\mu\varepsilon$. It is capable of making measurements at very high temperatures; estimates show that measurements are feasible on specimens as hot as 2000 °C. A feasibility study investigated theoretical aspects of using the system on small diameter wires and fibers at high temperatures,[4] and actual strain measurements were then demonstrated on wires and fibers as small as 76 µm in diameter. Unreported tests also show linear stress-strain measurements on 22 µm diameter PRD166 fiber.

The current system combines an improved compact optical system with the high performance digital processing system developed in Phase IV. The optical design allows two speckle patterns, which are necessary for measuring each strain point, to be recorded simultaneously on a single CCD array. This greatly decreases the measurement's sensitivity to rigid body motion, allowing potentially faster speckle pattern motions of greater magnitude to occur without degrading the accuracy of the measurement.

Similarly, simultaneous speckle pattern recording allows faster dynamic loading of the test specimen while acquiring the data. The technique uses two small, visible wavelength laser diodes to generate the speckle patterns, which contributes to the compact, easy-to-use size of the setup. This document describes the compact optical system and the stress-strain test results obtained in the laboratory.

SPECKLE-SHIFT THEORY

Laser speckle patterns, generated by the 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 2-D CCD sensor array before and after shifting, and cross-correlations of a single video line are calculated to determine the amount of shift between them.

A dual beam strain measurement automatically cancels error terms due to rigid body motion. These error terms are canceled by taking the difference in shifts of speckle patterns generated by two laser beams incident on the specimen from equal but opposite angles. Each laser beam generates a unique speckle pattern that moves when the material either moves (rigid body motion) or strains. By tracking the movement of the two speckle patterns and subtracting the distances they each moved, the movement due to rigid body motion is canceled and the movement due to strain is isolated.

Figure 1 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. Deformations of object points on the specimen surface are described by vector **a**(x,y), and the

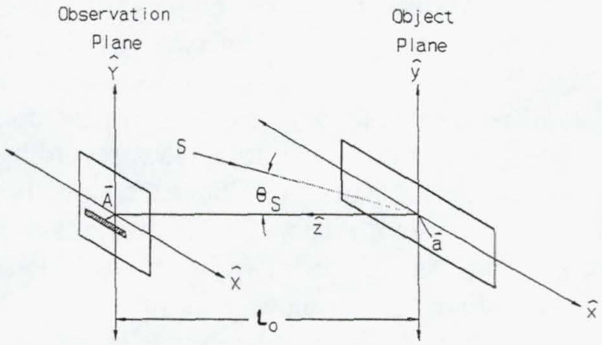

Figure 1: Simplified coordinate system

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 2D 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. The rigid body motion terms are canceled out of the simplified speckle-shift equations and the surface strain ε_{xx} in the x direction can be calculated by the relation:

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

where the incident angle $\theta = |\theta_S|$, L_0 is the free space distance separating the specimen from the CCD array, and ΔA_X is the difference between speckle shifts from the two beams

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

Each successive strain measurement thus requires a speckle pattern from each laser beam to be recorded. Each of these speckle patterns is then cross-correlated with its reference pattern to determine its shift. This reference pattern can be either an original speckle pattern recorded with the specimen in an unstrained state, or it can be updated to a recently-acquired shifted speckle pattern. In the latter case, the absolute strain is calculated by adding the incremental strains detected between each reference pattern update. This technique of updating the reference patterns extends the range of strain measurement in the presence of speckle pattern decorrelation, or large shifts in otherwise stable patterns.

OPTICAL SYSTEM

The two-beam/one-camera laser speckle strain gauge theory derived by Ichirou Yamaguchi requires, for each strain measurement, two independent speckle patterns to be recorded from the same specimen location. Prior art implemented the theory by either switching a single argon-ion laser beam from one beam path to the other, sequentially, or by using a separate helium-neon laser source for each beam path, again switching the beams on and off sequentially in order to only expose the camera with one speckle pattern at a time. Prior art, therefore, always acquired the two speckle patterns sequentially so that a single camera could record each speckle pattern separately.

A key improvement in the compact optical system is the ability to record the two distinct speckle patterns simultaneously, so that no relative speckle pattern movement can corrupt the measurement. In addition, a gated exposure can provide an exposure time short enough to prevent streaking of the speckle patterns in the event of fast rigid body motion transients or high strain rates.

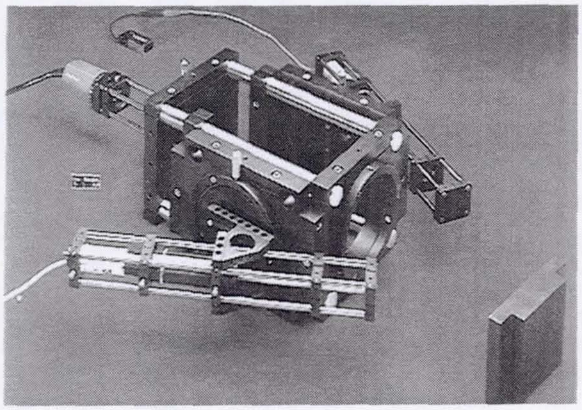

Figure 2: *Compact optical system*

Figure 2 is a view of the compact optical system, the design of which provides many improvements over previous systems: faster transient response, faster data acquisition, reduced size and weight, lower build cost, and lower complexity. The faster response is achieved by simultaneously recording the speckle pattern pairs on the same field of a single CCD camera. This reduces the time requirement for the speckle patterns to be stable from 66.7 ms (two RS-170 frames) to roughly 0.50 ms (1/2000 second exposure, which is a typical electronic shutter speed found on a CCD camera). In addition, the transfer of the video data to the computer is twice as fast, since only one video frame (or field) is needed. Also, the size of the compact optical system is more than one order of magnitude smaller and two orders of magnitude lighter than the previous system, allowing it to be mounted either onto a tripod, or directly onto a test rig. The cost of the compact optical system is roughly 20% of the previous designs' cost, bringing the total cost of the compact optical assembly to about $7,000. Finally, the reduced complexity of the compact system saves time in the setup and maintenance of the system; there are only half the optical components in the compact system, and no electronic controls are needed to switch the laser beams. The high speed image processing system performs the strain calculations in near real-time. The use of a two-dimensional charge coupled device (CCD) for the detector provides the flexibility of a standard RS-170 video interface.

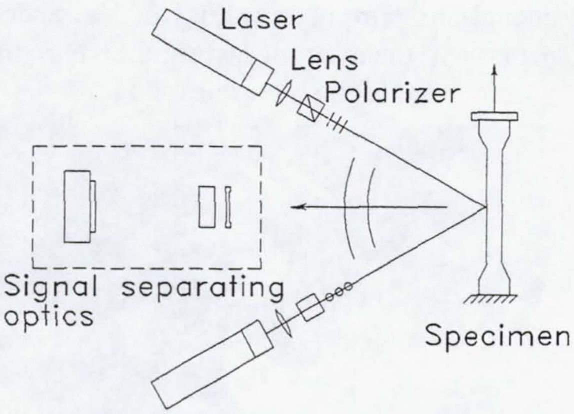

Figure 3: *Optical Schematic*

Figure 3 shows a schematic of the optical system. The two unique speckle patterns are generated by two visible-wavelength laser diodes illuminating a point on the test specimen symmetrically at angles of 30° from the surface normal. The lasers emit 20 mW of 680 nm visible light, rather than infrared light. The use of visible light aids in positioning the beams at the desired location on the specimen; this is important to the user-friendly philosophy of this system.

The strain-sensitive axis is defined by the intersection of the incident plane of the laser beams with the specimen surface (in the plane of this paper, parallel to the specimen axis in the figure). A lens system focuses each laser beam waist onto the specimen surface. The laser diodes have an index-guided structure, which minimizes the astigmatism in the beam. Beam circularizers (shown as integral to the lasers) convert the raw elliptical laser spots into roughly circular beams, so that the speckle statistics are similar in two dimensions.

The polarization vectors of the two laser beams are oriented 90° to one another, which generates speckle patterns with orthogonal polarizations. Polarizers are used to decrease the channel crosstalk; each beam should have a polarization purity of at least 300:1 for good signal separation. In the figure, the set of three lines on the top beam indicates a pure linear polarization state, and the three dots on the bottom beam indicate an orthogonal linear polarization state. Since cross-polarized light does not interfere, the light reflected off the specimen forms two superposed speckle patterns, one for each beam. These speckle patterns then propagate to the signal separating optics and are recorded by a CCD array camera.

Figure 4 shows a side view of detail of the signal separating optics (the sensitive axis is now normal to this paper's surface). A rectangular aperture is placed in front of the reflected light along the specimen surface normal, to allow only a narrow beam of the combined speckle patterns to reach the optics. The combined speckle patterns are then passed through a Wollaston polarizer, which introduces a small angle between the propagation vectors of the two polarized speckle patterns. After a short propagation distance the speckle patterns have completely separated from each other in space, and they illuminate a CCD array on which their intensity distributions are recorded. As figure 4 shows, each speckle pattern is directed to a different half of the CCD array - one speckle pattern to the top half, the other to the bottom half. This top/bottom orientation is not essential, but it has the advantages over a left/right orientation of finer pixel resolution (for most RS170 arrays) along the strain-sensitive axis of the instrument, and easier manipulation of the digitized data in the frame grabber memory (this memory is usually filled and accessed line by line). The relative orientation of the two orthogonal beam polarization vectors to the crystal axes of the Wollaston prism determine which speckle pattern falls on which portion of the array.

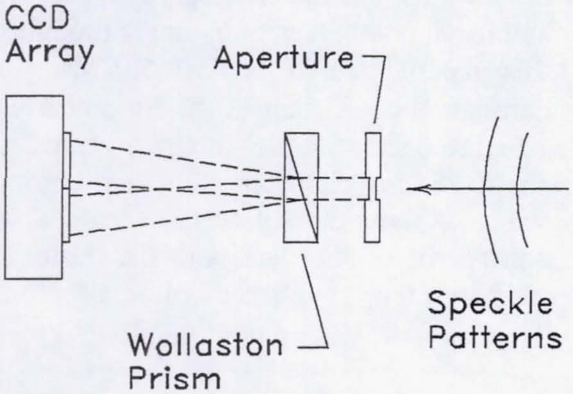

Figure 4: *Signal Separating Optics*

In the situation where the specimen material under test depolarizes the reflected light, one of two variations to the polarization technique can be used. The two lasers can be chosen to emit at different visible wavelengths, eg. 680 and 780 nm. In the first technique, appropriate interference filters can be positioned over the CCD array halves to filter out the depolarized light from the other laser source; otherwise the setup is unchanged.

A second alternative to either of the polarization separation techniques would be again to use a different wavelength for each laser beam, and to substitute a standard glass prism for the birefringent Wollaston prism. The glass prism would refract each color-coded speckle pattern to a different portion of the array, just as the Wollaston prism diverted each polarization-coded speckle pattern to a different portion of the array. The angular dispersion as a function of wavelength is given by[6]

$$\delta\phi = \frac{b}{w}\left(\frac{dn}{d\lambda}\right)\delta\lambda \qquad (3)$$

where b is the base length of the prism, w is the beam width, $dn/d\lambda$ for the glass is the first derivative of refractive index with respect to wavelength, and $\delta\lambda$ is the difference in wavelength between the two lasers.

Otherwise, the operation of this system would be virtually the same as with the polarization separation technique, but with greater channel separation while using depolarizing test specimens.

SYSTEM DESIGN

Test System

The data acquisition system is based on a high performance personal computer (Intel 80486 CPU), with a VGA graphics adapter using a graphics coprocessor. This PC synchronizes the acquisition of the video data and the load measurements with the strain calculations. The image processing system is comprised of a video camera, frame grabber and DSP board. The frame grabber and DSP board plug into the computer's 16-bit I/O bus (PC ISA bus). The DSP board performs the computationally intensive strain calculations using a floating point processor. The computer executes the control program, which is optimized to perform various overhead operations, while the image processor takes the speckle image data from the CCD array camera and correlates the images. An A/D converter digitizes the voltage across a load cell connected to the specimen mount. The test 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 software for the system is written in the C programming language. The time and temperature is also stored for each stress/strain point. The temperature is measured by either thermocouples or an infrared pyrometer.

RESULTS

Tests of the system demonstrated the tracking stability of the compact system, and its effectiveness in measuring accurate stress-strain curves for small diameter wires. The figures show optically measured strain values plotted against load. Past testing verified the accuracy of the speckle-shift technique in measuring strain on flat specimens, wire specimens, and fibers, and the test results presented here verify that the compact optical system is also operating at the expected level of performance.

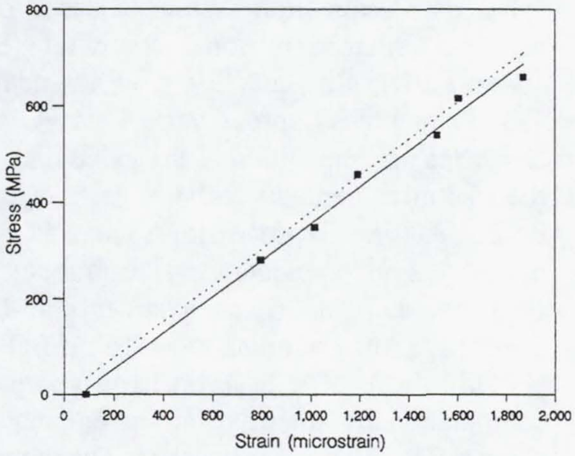

Figure 5: *Stress-strain plot for 76 µm diameter W-Re wire, at room temperature.*

Figure 5 shows a stress-strain plot for 76 µm (3 mil) diameter tungsten-3% rhenium wire measured at ambient temperature. The solid line indicates a least-squares linear regression of the data points. The dashed line represents the theoretical stress-strain curve whose slope corresponds to published values of Young's modulus for this material. Both the measured and handbook values of Young's modulus for this material are 379 GPa (55.0 Msi). The correlation coefficient of the fit is nearly 1.0.

Figure 6 shows a plot of stress versus strain for a 76 µm diameter palladium-chromium wire. Again, the solid line shows a least-squares fit of the data, and the dashed line indicates the published value of Young's modulus for PdCr wire. The measured modulus is 122 GPa (17.7 Msi), again, with a correlation coefficient of nearly 1.0. The estimated values of Young's modulus range from 119 - 124 GPa (17.3-18.0 Msi) for bulk PdCr, but no published values were found for drawn wire.

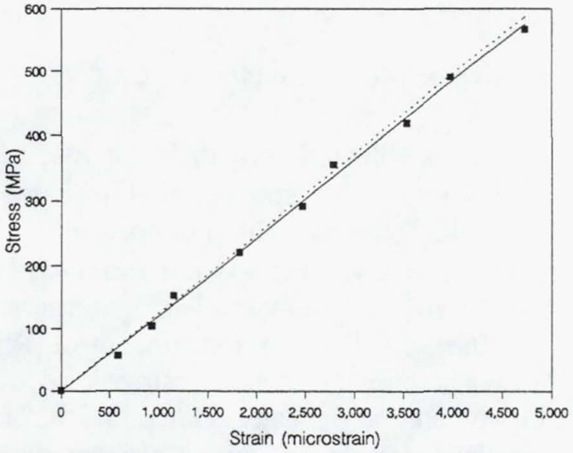

Figure 6: *Stress-strain plot for 76 µm diameter PdCr wire, at room temperature.*

Error Analysis

The measurement resolution of the system is determined from the geometry of the optical configuration, as described in equation 1. The values for the constants in equation 1 are: L_0= 612 mm; θ_S= 30°; ΔA_X= 8.7 µm. The value for θ_S was chosen as a compromise between resolution and compactness, and the value for L_0 is a reasonable distance determined, in part, by the optical mounting hardware. The minimum value for ΔA_X is determined by assuming a minimum detectable signal of one pixel of speckle pattern movement, with a pixel pitch of 8.7 μm on the sensor array. This leads to a strain value of 14 με as the resolution of the system. The resolution can be improved by various techniques, including sub-pixel position estimation through a curve-fit of the correlation peak.[7]

Small systematic errors come from the geometrical uncertainties in the optical setup, as described previously.[1] This systematic error in strain is given by the following total differential equation:

$$\partial \epsilon_{xx} = \frac{-\partial(\Delta A_X)}{2L_0 \sin(\theta_S)} - \left[\frac{\partial L_0}{L_0} + \frac{\partial \theta_S}{\tan(\theta_S)}\right] \epsilon_{xx} \,. \tag{4}$$

When compared to previous systems, one source of error has been eliminated by recording the speckle patterns from both beams simultaneously. If the patterns are not recorded simultaneously, the accuracy of the measurement is reduced by any strain or rigid body motion that occurs between the two exposures periods. The compact system eliminates any such error. Smearing of the speckle patterns that could occur during the measurement can be reduced by using a short exposure time on the video camera. Exposure times as short as 0.5 ms are easy to obtain with an RS-170 camera. This leads to an allowable strain rate of about 28,000 με/sec before speckle pattern smearing exceeds a magnitude equal to the strain resolution.

CONCLUSIONS

A compact optical design has provided many improvements to NASA's optical strain measurement system. Some of these improvements include portability, faster response, ease of setup and operation, lower cost, and greater reliability.

A disadvantage of the technique is that the signal separation is reduced when using depolarizing test specimens (eg. many ceramics). An alternative signal separation design is described which can eliminate this problem. This alternative design encodes the speckle patterns in two different colors of laser light, which are separated by a refracting prism in front of the video camera.

The compact system has been shown to provide accurate strain measurements at relatively fast measurement rates. Typical test data is presented from small diameter PdCr and WRe wire test samples.

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

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