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# AN INTERFEROMETRIC STRAIN/ DISPLACEMENT MEASUREMENT SYSTEM

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William N. Sharpe, Jr.

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**Langley Research Center**
Hampton, Virginia 23665

# AN INTERFEROMETRIC STRAIN/DISPLACEMENT MEASUREMENT SYSTEM

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ABSTRACT

A system for measuring the relative in-plane displacement over a gage length as short as 100 micrometers is described. Two closely spaced indentations are placed in a reflective specimen surface with a Vickers microhardness tester. Interference fringes are generated when they are illuminated with a He-Ne laser. As the distance between the indentations expands or contracts with applied load, the fringes move. This motion is monitored with a minicomputer-controlled system using linear diode arrays as sensors.

Characteristics of the system are: gage length ranging from 50 to 500 micrometers, but 100 micrometers is typical; least-count resolution of approximately 0.0025 micrometer; and sampling rate of 13 points per second. In addition, the measurement technique is non-contacting and non-reinforcing. It is useful for strain measurements over small gage lengths and for crack opening displacement measurements near crack tips.

This report is a detailed description of a new system recently installed in the Mechanics of Materials Branch at the NASA Langley Research Center. The intent is to enable a prospective user to evaluate the applicability of the system to a particular problem and assemble one if needed.

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# 1 Introduction

The Interferometric Strain/Displacement Gage (or ISDG) is a laboratory tool that measures relative displacements over gage lengths as short as 100 $\mu$m (gage lengths of 25 $\mu$m have been used) with a least-count resolution of approximately 0.0025 $\mu$m . The ISDG consists of two tiny indentations on a specimen, a laser, fringe intensity sensors, and a controlling microcomputer. It has the additional features of being non-contacting and non-reinforcing. Further, it has an extremely high frequency response when used for dynamic measurements and can be used in hostile environments such as high temperatures, corrosive atmospheres, or large electromagnetic fields.

These features make the ISDG useful in certain specialized studies of crack opening displacement and localized strain. Some earlier applications are described in a review article of 1983 [1], but there have been more experimental studies using the ISDG since then and further developments in the techniques. For example, several ISDG systems are routinely used at Wright Aeronautical Laboratories to measure the crack-opening-displacements of surface cracks and use that information to estimate the crack length as part of an automatic fatigue cracking system. Recent construction of a system at Johns Hopkins University that measures biaxial strains has enabled important new studies of plastic stresses under constrained yielding.

The purpose of this report is to present the basics of the measurement and describe a recently constructed ISDG system in the Mechanics of Materials Branch of the NASA-Langley Research Center in some detail. There is no commercial supplier, and the measurement system is sufficiently sophisticated that the individual user needs to understand it thoroughly. It is hoped that this report will present enough information that a potential user can make a judgement and construct a system if desired.

The basic optical principles are presented in the next section so that one can understand the physics of the measurement. It has been observed that, even though the principles are very simple, people tend to be confused as to whether it is fringe motion or fringe spacing that is measured. Some practical considerations based on the author's and colleagues' experience are then explained to aid the user. The computer-controlled system and two fringe sensor systems (the linear diode array system at Langley and the scanning mirror system at Hopkins) are then described in some detail. Finally, some examples of measurements are presented to give a feel for the capabilities of the ISDG.

## 2 Optical Principles

The basic optical principle underlying the Interferometric Strain/Displacement Gage is interference of two diffraction patterns emanating from indentations on the specimen surface. It is simply the familiar Young's two-slit interference phenomenon, as shown schematically in Figure 1, except that the light rays are reflected from two small surfaces instead of passing through two narrow slits. The following sections describe the optical principles as they apply to the ISDG. The reference for this discussion is the well-known text, Fundamentals of Optics by Jenkins and White [2], but any elementary optics book would serve as well.

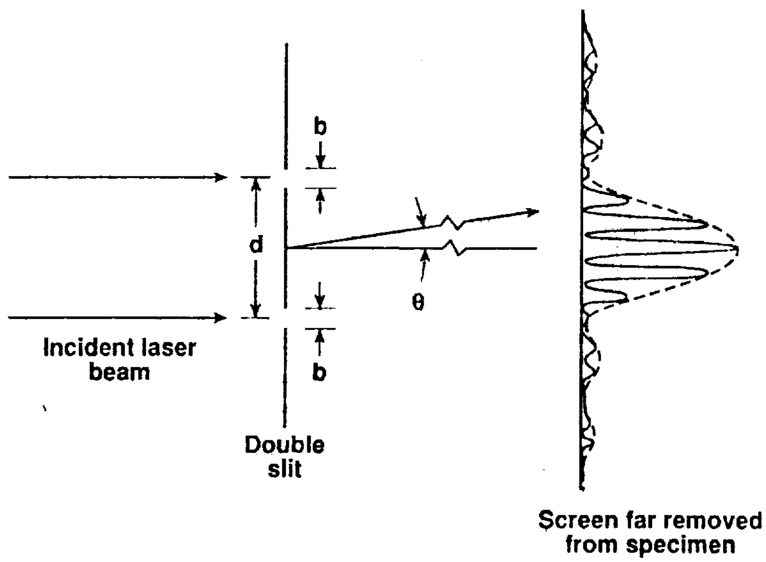


Figure 1. Schematic of the double-slit interference phenomenon. 'b' and 'd' are the slit widths and spacing respectively. $\theta$ is the angle between a line parallel to the incident laser beam and a position on the screen. The distance between the slits and the screen is many orders of magnitude greater than 'd'.

### 2.1 *Diffraction*

Diffraction of waves — light waves for example — occurs when the wave encounters a stop or aperture that is similar in size to the wavelength of the radiation. Diffraction of a wave passing through an aperture causes the exiting wave to spread according to the following equation:

$$I = I_o sin^2\beta/\beta^2 \tag{2.1}$$

with $\beta = \pi b sin\theta/\lambda$. $\lambda$ is the wavelength, and $b$ is the dimension of the aperture. The incident beam is collimated with intensity $I_o$, and the intensity, $I$, of the exiting beam varies with the angle $\theta$.

The intensity has a first minimum at $\beta = \pm\pi$, and most of the energy of the radiation is included within this range. So, the 'width' of the diffraction pattern is given by

$$sin\theta = \lambda/b. \tag{2.2}$$

For $\lambda/b = 0.1$, the half-angle spread is 5.7 degrees which is quite appreciable. The wavelength of radiation from a He-Ne laser is 0.6328 $\mu$m so that a 6 $\mu$m slit would spread the exit beam a total of 12 degrees. Even a 60 $\mu$m slit would spread the beam 1.2 degrees.

Slits are not used for the ISDG, but the diffraction arises from the reflection of the incident laser beam from small indentations. A Vickers microhardness tester is typically used to apply the indents, and Figure 2a is a photomicrograph of a single indentation. Figure 2b is a photograph of one of the resulting diffraction patterns (there are four patterns from the four sides of the indentation) which is triangular in shape as expected.

The indentation in Figure 2a is approximately 25 $\mu$m square. The included angle of the Vickers diamond is 136 degrees, so the length of a reflective side (the maximum dimension of a triangular surface pressed into the material) is approximately 13.5 $\mu$m . Therefore $\lambda/b$ is 0.047, and the total angle of diffraction is 5.4 degrees. The diffraction pattern of Figure 2b is full-size and was photographed with the film plane approximately 30 cm away from the indentations. It should be about 2.9 cm long, which the brightest portion is.

## 2.2 Interference

When two slits are illuminated by coherent monochromatic light, the spreading diffracted beams from each slit overlap to form an interference pattern if the slits are close enough together. The equation governing the spacing of the interference fringes is

$$I = I_o cos^2\gamma \tag{2.3}$$

where $\gamma = \pi d sin\theta/\lambda$. The spacing between the two slits is 'd'. The interference pattern has a minimum whenever $\gamma = \pi/2, 3\pi/2, 5\pi/2, \ldots.$ So, the spacing between interference fringes is given by $sin\theta = \lambda/d$.

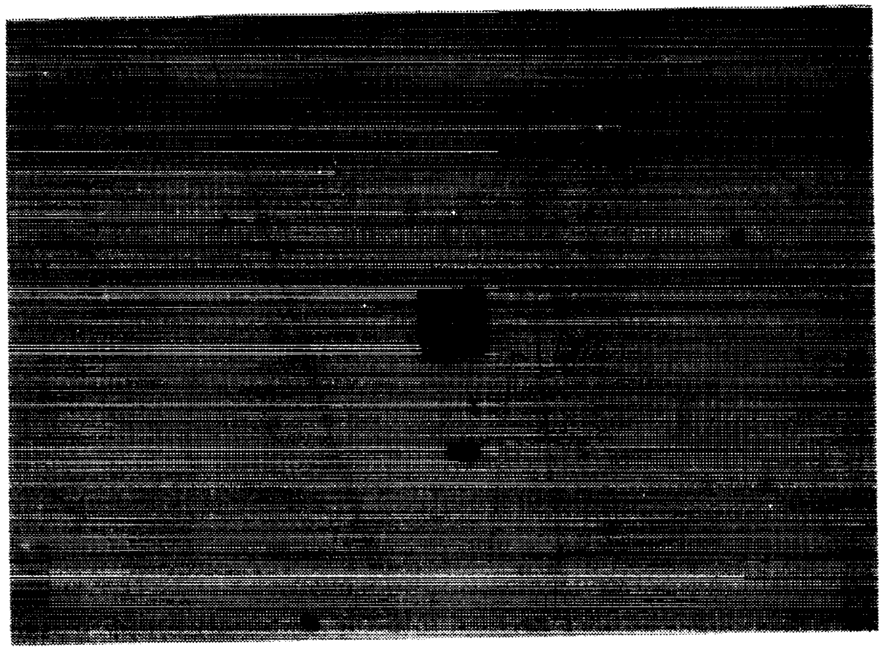

Figure 2a. Photomicrograph of a single indentation applied with a Vickers microhardness tester. The indentation is approximately 25 $\mu$m square.

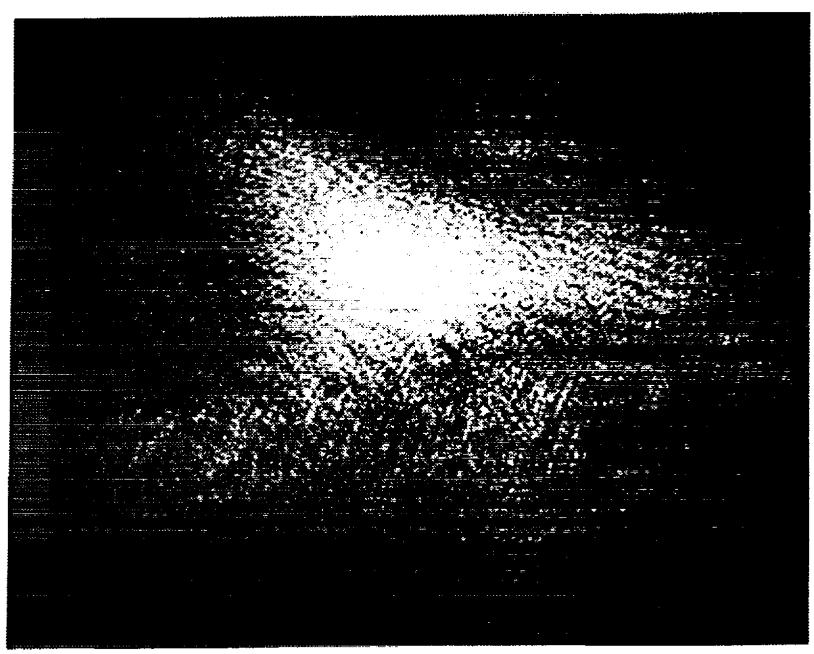

Figure 2b. Photograph of a diffraction pattern from the indentation in Figure 2a. The photograph is full size, and the film plane was located 30 cm from the indentation.

A complete description of the two-slit diffraction/interference pattern is therefore given by:

$$I = I_o sin^2\beta/\beta^2 \times cos^2\gamma. \tag{2.4}$$

The angular width of the principal maximum of the diffraction pattern is given by $\lambda/b$ and the angular spacing between interference fringes by $\lambda/d$.

Figure 3a is a photomicrograph of a pair of indentations located 100 $\mu$m apart; Figure 3b is a photograph of the resulting pattern. The value $\lambda/d$ is 0.006328, so the spacing between fringes is predicted to be about 0.4 cm.

Figure 4 is an intensity plot of the patterns in Figures 2b and 3b taken with a linear diode array. It shows very clearly the difference between the diffraction and the interference patterns and is a graphical representation of Equation 4. The plot in Figure 4 is similar to the sketch at the right side of Figure 1.

### *2.3 Relative Displacement*

The position, $\theta$, of an interference fringe, '$m$', is given by

$$(m + 1/2)\lambda = d\ sin\theta;\ m = 0, 1, 2, 3, ..... \tag{2.5}$$

when the two slits or indentations are 'd' apart. '$m$' is the 'order' of the fringe and identifies each individual one. Note the similarity between this equation and Bragg's Law of X-ray diffraction.

If 'd' changes a small amount, $\delta d$, the angular location of a given fringe moves by

$$\delta\theta = -\delta d/d \times sin\theta/cos\theta. \tag{2.6}$$

Note that the shape of the diffraction envelope has not changed because 'b' has not changed. So, a relative displacement between the two slits causes the fringes to move within the diffraction envelope.

The ISDG is therefore an interference-based gage because the relative motion causes shifts in the interference pattern. The diffraction simply causes the light rays reflected from the indents to spread enough to overlap and form the interference patterns. If one observes the fringe pattern as the two slits or indents move, one sees no change in the overall diffraction pattern, but sees the interference fringes moving within the diffraction pattern.

It would be possible to use a detector to identify a particular interference fringe and physically move the detector with the fringe as the distance 'd' changes. The angular location of the detector would then be proportional to the relative displacement of the

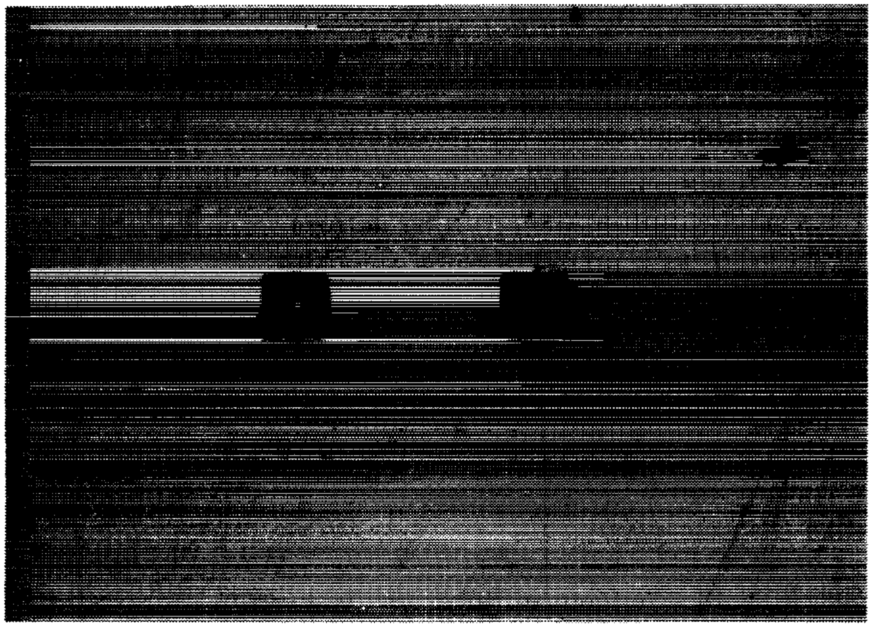

**Figure 3a.** Photomicrograph of a pair of indentations 100 $\mu$m apart.

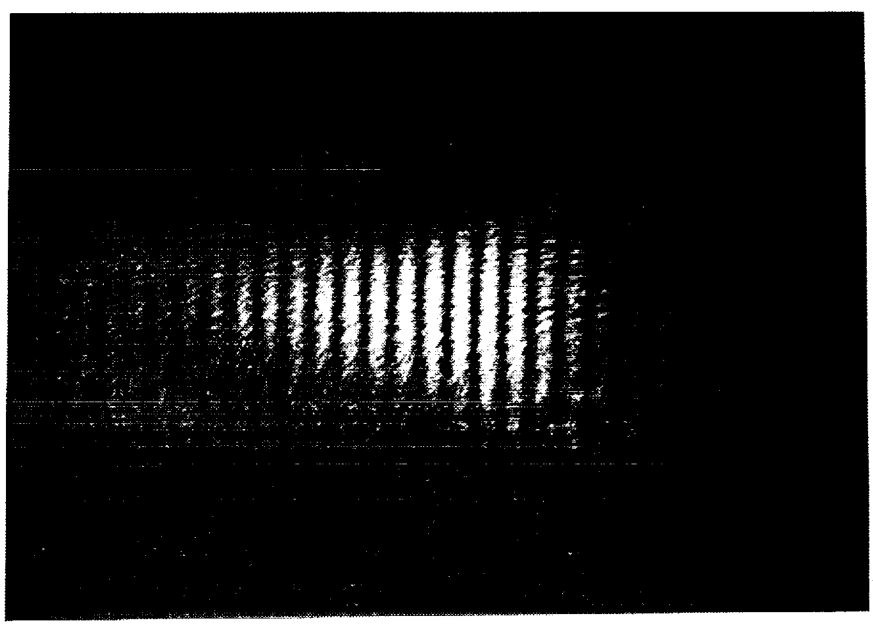

**Figure 3b.** Photograph of an interference pattern from the two indentations in Figure 3a. The photograph is full size, and the film plane was located 30 cm from the indentations.

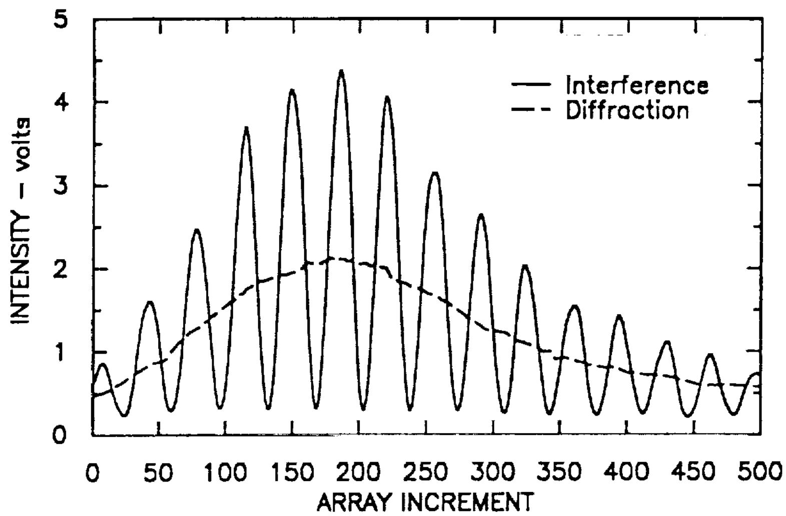


Figure 4. Intensity of the diffraction and interference patterns of Figures 2b and 3b as a function of angle. These were measured with a linear diode array so that array increment is proportional to the angle.

indents. This is inconvenient; it is easier to use a detector fixed in space and record the fringes as they move by. What one then observes is a change in the fringe order, i.e. one might start with the detector on the minimum with order 37 (for example) and watch the intensity increase to a maximum and then decrease back to a minimum — say 38. This shift of an adjacent fringe to the observation position would correspond to $\delta$m = 1. Since it is the order that is changing ($\delta m$) at a given position ($\theta$) rather than the position changing ($\delta\theta$) for a given order ($m$), the governing equation is now:

$$\delta d = \delta m\, \lambda / sin\theta, \tag{2.7}$$

and this equation is the basis for the various versions of the ISDG.

$\delta m$ is the amount of relative fringe motion as a fraction (or multiple) of the spacing between fringes. $\delta m$ can be measured very simply with a pencil, ruler and screen, and it is perhaps instructive to describe that procedure. Imagine an indented specimen mounted in a tensile testing machine and illuminated with a laser. In a dark room with a 5 milliwatt He-Ne laser, the fringes would be easily visible on a white screen placed placed, say, 50 cm from the specimen. Select three fringes (call them 1,2,3) in the middle of the pattern and draw lines on the screen corresponding to them. Measure the spacing between Fringes 1 & 2 and 2 & 3 with the ruler (the spacing should be equal) and call it 'X'. Next, apply a slight load to the specimen so that the fringes move. Draw a line through the new position of the middle fringe, (2), and measure the distance between this new position and the original position; call it 'x'. The relative fringe motion is $\delta m$ = x/X. If the load is increased enough that fringe 1 moves into the position formerly occupied by fringe 2, then $\delta m = 1$. If the load is increased further, one simply repeats the process, but now $\delta m = 1 + x/X$. This can be repeated for higher loads and more fringe motion. Though simple, this is exactly the strategy used with the computer-controlled detector system described later in this report.

The fringes not only move, but the spacing between them changes although this is a smaller effect. The angle between fringes can be computed by differentiating the governing equation with respect to $m$ and $\theta$ to yield

$$\delta m\ \lambda = d\ cos\theta\ \delta\theta. \tag{2.8}$$

Set $\delta m = 1$ to obtain the spacing between adjacent fringes, and

$$\delta\theta = \lambda / dcos\theta. \tag{2.9}$$

It is clear from the fringe motion measurement procedure described above that the computation of $\delta m$ must be based on the current spacing between fringes and not on the original spacing.

## 2.4 *Strain*

The equation for strain measurement is

$$\epsilon = \delta d / d_o = \delta m\ \lambda / d_o sin\theta_o \tag{2.10}$$

where $d_o$ is the gage length between indentations and $\theta_o$ is the observation position. ($\delta m$ is actually an average of two fringe pattern motions as will be discussed later.)

The 'calibration factor' is $\lambda / sin\theta_o$. The wavelength of a He-Ne laser is 0.6328 $\mu$m, and the reflection angle from indents produced with a Vickers microhardness tester is approximately 42 degrees so that the calibration factor is 0.95 or approximately 1. Therefore a $\delta m$ of 1 corresponds to a relative displacement of approximately 1 $\mu$m. A typical gage length is on the order of 100 $\mu$m; the corresponding strain would be 0.01. This is too large for elastic strain measurements on metals, so a microcomputer-controlled detector system is used to measure small relative fringe motions. It is described in a later section and can have a least-count strain output as small as 0.000025 (25 microstrain).

## 2.5 *Displacement*

Displacement measurement across fatigue cracks is a common application of the ISDG, and the equation is

$$\delta d = \delta m\ \lambda / sin\theta_o. \tag{2.11}$$

A relative fringe motion of one therefore corresponds to a displacement of about 1 $\mu$m. It is easy to record $\delta m$ in increments of 1/2; those are simply maximums. One can record the intensity on a stripchart recorder and analyze the record afterwards or use a microcomputer-controlled system that monitors the signal and identifies changes in signal slope. In dynamic displacement measurements, the fringe intensity is recorded on an oscilloscope.

### *2.6 Closing*

The important thing to remember here is that it is the interference and not the diffraction patterns that move. The spacing of the fringes changes very little as the indents separate (as will be shown in a later section). One measures the movement of the interference fringes, and a shift of one fringe corresponds to a relative displacement of about 1 $\mu$m . In a very real sense, the ISDG is simply an optical lever with the 'mechanical advantage' coming from the interference phenomenon.

## 3 Practical Considerations

An understanding of the underlying principles of the ISDG is necessary of course, but there are many practical aspects of its use that are gained only with experience. This section discusses practical considerations associated with producing a useable fringe pattern at a detector. As with any measurement system, the better the initial signal, the easier it is to generate a useful output. The objective in preparing a specimen and arranging an optical system is to produce fringe patterns that are as good as those in Figure 3b.

### *3.1 Surface Preparation*

A flat metal surface polished to a mirror finish will yield the best fringe patterns from indentations; the photographs of Figures 2b and 3b and the plot of Figure 4 were taken from indents on a polished steel specimen. Such a high quality surface finish is not always possible because some materials don't polish as well. Also, many applications of the IDSG have been for strain and displacement measurements at notch roots which are difficult to polish.

Quite acceptable fringe patterns can be generated from surfaces polished with 600 grit sandpaper. Figure 5a is a photomicrograph of such a surface, and Figure 5b is the corresponding fringe pattern. The pattern is considerably degraded, but similar fringe patterns have been used successfully. The main difficulty with such a surface is the reflections from the scratches, but if the scratches are parallel to the line between the indents, then the stray reflections do not fall in the fringe pattern. The scratches in Figure 5a would not degrade the fringe pattern. However, they may reflect from other parts of the system, so optical shielding would probably be needed.

Some materials are not reflective and some surfaces are too rough to be polished. Attachable ISDG indentations have been developed which can be applied like foil resistance strain gages. In one version, acetate replicas are made of master indentations; the replica is coated to make it reflective and glued to the specimen. In another version, a thin foil is glued to the specimen and the foil then indented. Both techniques are described in [3].

### *3.2 Indentors*

An instrument for applying the indentations must be capable of optical magnification on the order of 200X to locate the site of the indent. It must then be able to impress an indent of a specified size to within a $\mu$m or two of that site. The familiar microhardness tester does this very well. The ISDG can be applied to a variety of specimen shapes and sizes, and it is desirable to have a microhardness tester that has flexibility in this regard. Some microhardness testers are designed specifically to accomodate metallurgical specimens in plastic mounts and are limited in the size of specimen that can be accomodated. Testers made by Leitz are very flexible, and the ones made by LECO will accomodate most specimen sizes.

The diamond in a microhardness tester is oriented so that the diagonals of the square indentation (with a Vickers diamond) are parallel to the translation stage axes. This is inconvenient for ISDG indents; one wants the sides of the indents parallel to the axes. The diamond can be removed and rotated 45 degrees. The precise orientation is achieved by trial and error and can be tedious, so it is better to have a tester dedicated to indent application.

A Vickers diamond has an included angle of 136 degrees, so the angle of reflection is 44 degrees from an incident laser beam that is perpendicular to the specimen surface. A weight of 100 or 200 grams will produce indentations on the order of 20 $\mu$m square in aluminum and steel respectively. The weight can be selected by test indents on a remote portion of the specimen.

It is possible to have diamonds custom-made at a cost of several hundred dollars for special applications. For example, to put indents at the roots of 4.76 mm notches in fatigue specimens, a Vickers diamond with an extended shank was purchased from F. F. Gilmore Co. of Needham Heights, MA. It is also possible to make one's own indenting apparatus using a stereo microscope, translation stages, and some mechanism for lowering the weighted diamond onto the specimen.

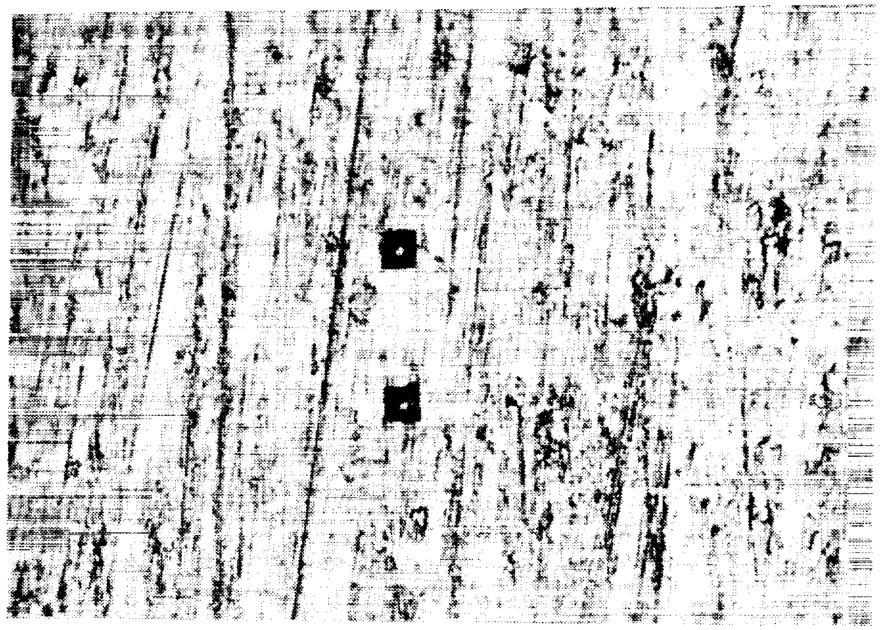

Figure 5a. Photomicrograph of a pair of indentations in aluminum polished with 600 grit sandpaper.

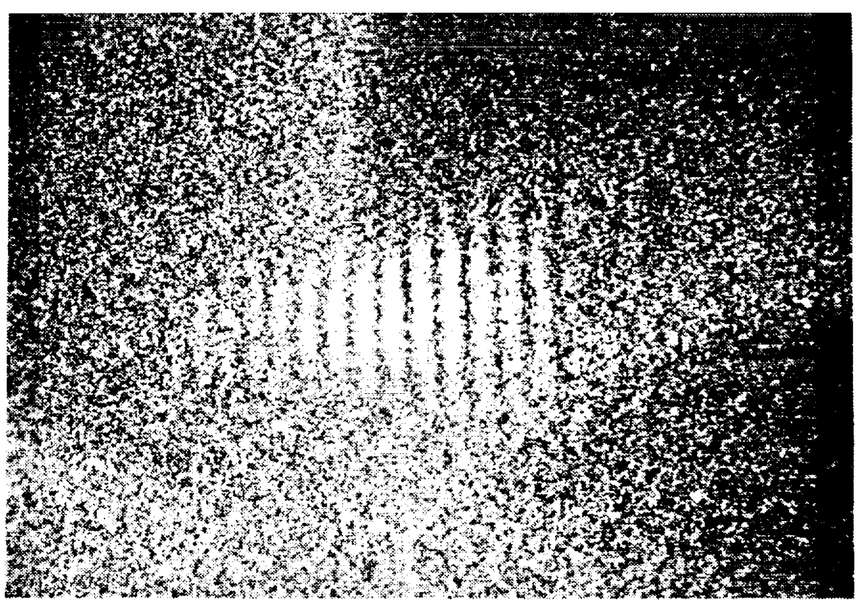

Figure 5b. Photograph of the fringe pattern from the indentations in Figure 5a.

It is perhaps surprising to learn that the diamond indentors can get dirty. Poor fringe patterns sometimes arise because of the dirty sides of the indents when the dirt comes from an unclean surface. This is transferred to the diamond. A diamond may have a rough edge at one of the corners of the pyramid, and this can trap bits of the specimen metal. This metal can usually be scraped off with a fingernail, and the diamond can be cleaned with acetone. It is sometimes necessary to remove the diamond and inspect it with a stereo microscope to assure its cleanliness.

### *3.3 Laser Intensity*

A typical set of indentations is spaced 100 $\mu$m apart with each indent approximately 20 $\mu$m square. If these are in a reflective metal like aluminum, then a small He-Ne alignment laser with intensity less than 1 milliwatt will produce fringe patterns that are easily visible in a dark room. In fact, the photographs in Figures 2b and 3b were taken from slightly larger indents illuminated with a 0.95 milliwatt laser.

It is preferable to work in a dimly lit area rather than a very dark room, so a larger laser is preferable. Further, a specimen will move when it is loaded in a testing machine, so it is necessary to have a reasonably large diameter of the laser beam incident on the specimen. This, naturally, reduces the intensity of the fringe pattern. Most of the applications of the ISDG have used He-Ne lasers of 5 milliwatt intensity, but lasers with 10 to 15 milliwatt intensity are quite useful. One can always reduce the brightness of the laser beam with a variable neutral density filter. A 250 milliwatt argon laser has been used for a high temperature application of the ISDG [4].

Often, the laser beam is actually larger than needed and can be focused with a spherical lens to a smaller spot. This is useful when sets of indents are placed closely together to study strain gradients. One can also use a cylindrical lens to compress the beam in one direction so that the indents do not move out of the beam when the specimen is loaded.

Safety is a major consideration. Even though the smaller lasers don't require special precautions or warnings, they can still damage the eye. The main source of problems is stray reflections from other parts of the optical system or from rings, watches, etc. The specimen is often highly polished and can reflect the laser beam in unexpected directions during setup. The fact that the pupil of the eye is enlarged because of the dim light around the setup increases the danger of eye damage. Working with lasers as powerful as 15 milliwatts can be done safely and comfortably if reasonable care is taken.

### *3.4 Spacing Between Indentations*

The ISDG has been used with indents as close together as 25 $\mu$m and as far apart as 5 mm. The angular spacing is given by

$$\delta\theta = \lambda/d\ cos\theta \tag{3.1}$$

For $\lambda = 0.6328\mu m$, $d = 100\mu m$, and $\theta = 42$ deg, the angular spacing, $\delta\theta$ is 0.0085. If a screen is placed 100 cm from the indents, the spacing between fringes would be 8.5 mm. This is fairly large, but works nicely if the detector is a photomultiplier tube with a large aperture. One can always vary the spacing by moving the screen, or, if a scanning mirror is used, varying the amplitude of the scan. From past experience, indentation spacings of 100 to 200 $\mu m$ turn out to be convenient in terms of the physical setup of the instrumentation. Different spacings can be accomodated by different arrangements of the detectors.

### 3.5 *Optical Shielding*

Since the specimen surface is likely to be reflective, but not perfectly smooth or flat, the incident laser beam that overlaps the indents is reflected back toward the laser at various angles. These stray reflections can fall in the fringe pattern or onto the detectors. This problem is usually remedied by placing stops or shields of black cardboard at appropriate places.

It is perhaps most convenient to have the ISDG measurement system in a completely dark room so that dim patterns from small indents, low-power lasers, or low-reflectivity surfaces can be seen. However, the fringes are normally bright enough to be seen in a dimly lit area. Interference optical filters for the specific laser wavelength can be put over the detectors so that the test can be run in full room light provided that none of the room lights shine directly onto the detector. A dimly lit area is needed to set up the experiment, arrange the fringes on the photodetectors, and check for stray reflections. The ISDG system at NASA-Langley is housed in a tent of black cloth in the fatigue laboratory.

The laser light, because of its high degree of coherence, generates speckles or interference spots whenever it reflects from a surface that is not perfectly smooth. These speckles can be seen in Figure 3b in the region surrounding the fringes. If the detector has a small aperture, these speckles contribute noise to the signal. This noise can sometimes be eliminated by covering the detector with transparent, but diffuse, cellophane tape such as "Magic Mending Tape". Figure 6 is a plot of a poor fringe pattern signal that is improved by covering a linear diode array detector with tape. The tape diffuses the speckles so that the detector sees a smoother pattern.

### 3.6 *Rigid Body Motion*

The interference fringes, as observed on a screen or detector, will obviously move if the indents undergo any rigid body motion. Indents on a specimen loaded in a test machine

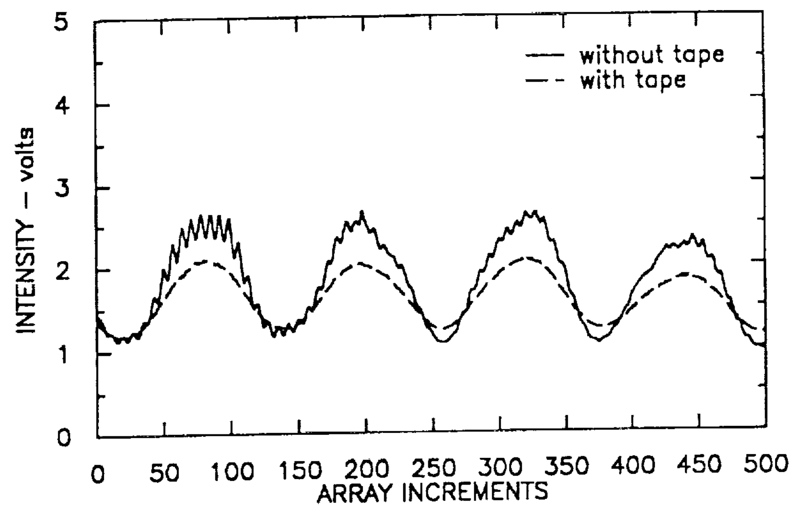


Figure 6. Intensity plot showing the improvement in pattern smoothness obtained by covering a linear diode array with diffuse tape.

will move due to the stretching of the specimen as well as the elastic linkages and grips.

Figure 7 is a schematic defining a coordinate system for the purposes of discussion. The specimen is loaded in the Z direction, so the indentations will move vertically due (at least) to the stretching of the specimen. Define positive fringe motion as toward the incident laser beam as shown in Figure 7. Equation 5 shows that this corresponds to tensile separation of the indents; as $d$ gets larger, $\theta$ must get smaller for a given fringe order. One sees from Figure 7 that vertical rigid body motion (with no strain) will cause a positive motion of one fringe pattern and a negative motion of the other.

The equation that must be used for the ISDG is therefore:

$$\delta d = (\Delta m_1 + \Delta m_2)/2 \times \lambda / sin\theta_o \qquad (3.2)$$

where $\Delta m_1$ and $\Delta m_2$ are the motions of the two fringe patterns.

A rotation about the X axis will be averaged out also. Movement along the X axis will have no effect since the fringes are parallel to it. Rotation about either the Z axis or the Y axis will cause the fringes to move parallel to themselves as long as the center of rotation is at the indentations.

The most troublesome rigid body motion is along the Y axis since both fringe motions have the same sign. The Poisson effect will generate displacement in that direction, but a simple calculation shows it to be small. In the above discussion on fringe spacing, it was shown that indents 100 $\mu$m apart would generate fringes 8.5 mm apart on a screen located 100 cm away. Suppose those indents were on an elastic specimen 25 mm wide and loaded to a strain of 0.01. The fringe motion on the screen would then

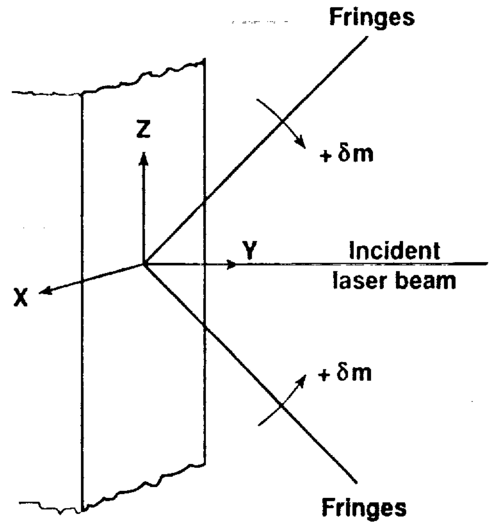


Figure 7. Schematic defining the coordinate system for the discussion of rigid body motion. The origin is at the indentations.

be approwimately 8.5 mm as a result of the straining. The fringe motion due to the Poisson effect would be a projection of that displacement of the specimen surface. If Poisson's ratio is 0.3, the displacement in the Y direction is $0.01 \times 0.3 \times 25\text{mm}/2 = 0.038$ mm. When projected, it is about 0.03 mm which is less than 1/2 percent of the fringe motion due to the strain.

Motion in the Y direction, as well as other components, is likely to come from imperfect alignment of the testing machine. However, experience with the ISDG on a number of different electrohydraulic test machines has shown no serious problems. In a practical sense, the ISDG can be used on a typical test machine if the load cell, ram, and grips are carefully aligned. It is wise to conduct some elastic checks by comparing ISDG strains with foil gages strains when setting up in a different machine. The amount of specimen displacement can be easily checked with a dial gage.

Rigid body motion is a real problem if one tries to measure strains on a curved surface. The rigid body motion of the indents is difficult to predict or measure. Perhaps it is possible to use the other two fringe patterns and even the diffraction envelope of the two primary patterns to monitor the motion of the indents, but this has not been tried. Crack opening displacement measurements are less sensitive to rigid body motion because the amount of fringe motion is so much greater.

# 4 Computer Controlled System

It is necessary to measure small increments of fringe motion in order that the ISDG can be used for strain and small displacement measurement. This is done most easily with a computer controlled system such as described in this section. With it, one can measure fringe increments of approximately 1/100 at rates of approximately 10 data points per second. The ISDG could be used simply as a stand-alone instrument, but it is more convenient to use the same computer to simultaneously control the experiment.

A schematic of the ISDG measurement and test control system is given in Figure 8. The computer takes data from the two sensors and processes it to locate the positions in the data array of the fringe minimums. It then sends a signal to the actuator to change the load on the specimen and repeats the fringe data acquisition and analysis. By comparing the location of the fringe minimums before and after the load change, it can compute the amount of relative displacement. The load and relative displacement are then stored by the computer, and they are usually output to a plotter so that one can monitor the experiment.

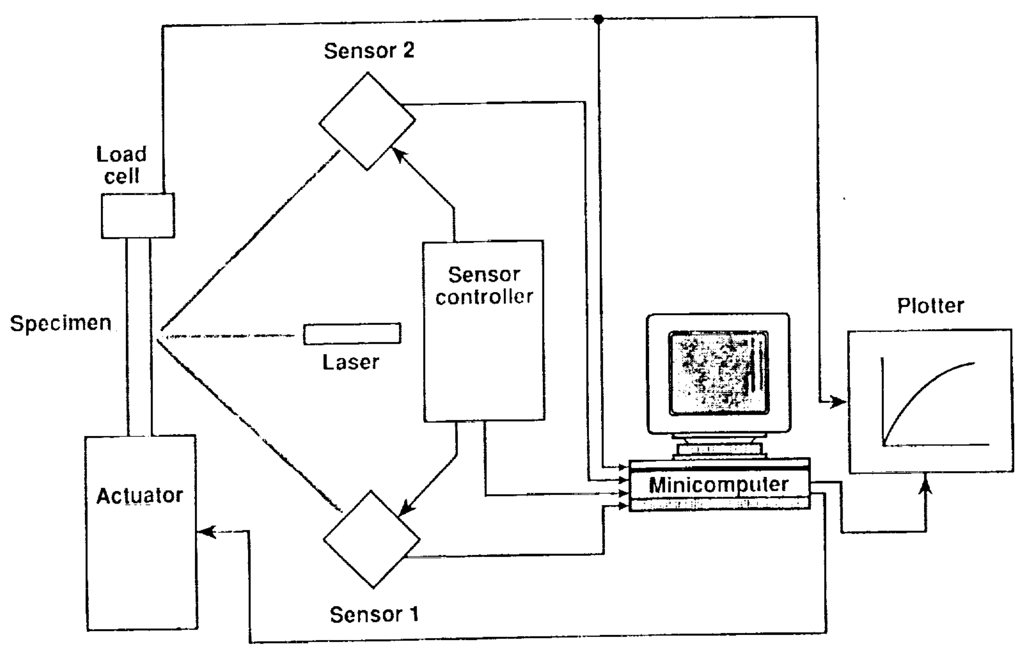


Figure 8. Schematic of the computer controlled ISDG system. Signals from the two sensors and the load cell go into A/D channels of the microcomputer. The signal from the sensor controller goes into the external trigger channel. D/A output signals go to the test machine actuator and to the plotter.

This section discusses the hardware and software of the microcomputer system. There are two kinds of fringe sensors: linear diode arrays and scanning mirrors with photomultiplier tubes. These are discussed in the following two sections.

### *4.1 Hardware*

The microcomputer is a PC compatible with slots to accomodate a data acquisition board. The model in the NASA-Langley system is a CompuAdd 286/10 with a 20MB fixed disk and a diskette drive using 5.25 inch double-sided/high-density diskettes holding up to 1.2 MB of data. It runs the 80286 microprocessor at speeds of either 6 or 10 MHz. It has a 14 inch EGA color monitor and interface and is loaded with MS-DOS version 3.3.

The microcomputer is equipped with one model DT 2821-F-8DI A/D and D/A board from Data Translation, Inc. It has eight channels of differentially connected A/D input, two channels of D/A output, two 8-bit channels of digital I/O, and provisions for external trigger and external clock. The A/D throughput is 150 kHz, and the D/A throughput is 130 kHz.

### *4.2 Software*

Data acquisition and control is programmed in FORTRAN and uses the ATLAB assembly language subroutine library from Data Translation, Inc. The most recent version is 01.10 which requires Microsoft FORTRAN version 4.1. The earlier version of ATLAB, 1.0 compiled with Microsoft FORTRAN version 3.3.

The locally written programs for acquiring the fringe intensity, computing the relative displacement, and controlling the loading are described in the following two sections as they are used with the linear diode array fringe sensors. They would need to be slightly modified to accomodate the scanning mirror and photomultiplier tube sensors. Copies of the data acquisition and control programs are contained in the Appendix.

#### *4.2.1 Setup Program — PREVIEW*

The fringe intensities are usually displayed on a two-channel oscilloscope for ease in adjusting the laser beam and aligning the sensors. But it is convenient to scan the sensors, display, and possibly store the fringe signals on the computer as part of the setup process. PREVIEW is a short program that does just that. First, it asks for the frequency, RATE, at which the arrays are being scanned (this is discussed later in the section on the linear diode arrays). It then takes the data for both channels with the Data Translation board operating in the burst mode on external trigger from the diode array controller. This routine, ALBAD, writes the data sequentially and alternately into a buffer, BUF1, at the specified frequency. The buffer is 1024 long to accomodate the two 512 pixel arrays of the linear diodes.

Once the two fringe patterns are stored in the buffer, they must be taken out for processing; one pattern is the odd numbers, AV1(500), and the other is the even numbers, AV2(500). It has been found useful to do some digital filtering of the data by using a sliding average, and PREVIEW permits one to not average at all or to average over 10 points. It should be noted that the testing program described below uses 10-point averaging. The fringe data can be saved into a file if desired. PREVIEW then scans through the data array of each channel and finds the minimums — up to six. The minimums are found by comparing the sign of the difference between two values in the array that are 8 positions apart. When this sign (i.e. the slope of the curve) changes from negative to positive, a minimum has been found, and the location in the array is recorded.

PREVIEW plots the recorded fringe intensities and the locations of the minimums on the color monitor; it also prints the minimum locations. The plot routine is made up from a FORTRAN-callable graphics package entitled GRAFMATIC available from Microcompatibles, Inc. of Silver Spring, MD.

### *4.2.2 Test Programs — ISDGSS and ISDG*

There are two programs for testing: ISDGSS loads the specimen through one cycle and stores each data point to disk as it is taken; ISDG loads through several cycles and stores the data at the end of each cycle. The usual procedure is to run ISDGSS for the first cycle in case anything strange happens and then run ISDG for the rest of the cycles.

The various components of either program are:

1. Dimensions for ATLAB as well as for computation.

2. Test information to be written to a separate header file and the name of the data file.

3. Specification of the loading path — Triangular or sine shape with R = 0.5, 0, -1 — and creation of the load output signal array.

4. Ask whether to:

    (a) Calibrate strain gage (one channel of foil gage data can be taken)

    (b) Run VIEW — to check the minimum locations

    (c) Run STRAIN2 — the actual test

    (d) Abort

5. VIEW
6. STRAIN2

### *4.2.3 VIEW Subprogram*

VIEW searches for the minimums using positions obtained in PREVIEW. PREVIEW scans the entire data array for the minimum locations, but the test programs search the arrays only in the neighborhood of the previously identified minimums. This is a way of labelling the individual minimums as well as saving some computational time. VIEW acquires the fringe intensities and splits them into the two arrays AV1 and AV2. It then calls a subroutine FRGC which manages the minimum searches for both channels. Minimums are found by a subroutine MINC2 which will be discussed below.

### *4.2.4 STRAIN2 Subprogram*

STRAIN2 opens the data and header files and writes the test information to the header file. It then goes through the following steps for each set of load, strain, foil gage data:

1. ISDGSS writes to the color monitor the step number and the locations of the two central minimums. ISDG writes only the cycle number.
2. Acquire the fringe data into the buffer.
3. Acquire the load cell voltage.
4. Acquire the foil strain gage voltage (if used).
5. Send out the load signal on D/A # 0.
6. Split the buffer data into AV1 and AV2; using 10-point averaging.
7. Call subroutine DISPL2 twice to find the current minimum positions and the updated total displacement for channels 1 and 2.
8. Compute the final strain by averaging the displacements from both channels.
9. Send out a voltage on D/A # 1 proportional to the strain; this is used to drive the X axis of an XY plotter which has the load cell connected as the Y axis.
10. Store strain, load, and foil gage voltage.

Data is stored in direct, unformatted binary form with each data point taking 2 bytes. ISDGSS also stores the step number, so the record length is 8. If NOS is the number of steps in a cycle, then the record length for ISDG is (NOS*3 + 4)*2 — 2*3 for the 3 data points associated with each step plus 8 for the cycle number.

### 4.2.5 *Subroutine DISPL2*

DISPL2 follows a central minimum, MCC, and the two minimums on either side, MLC and MRC, for each fringe pattern. It is convenient to arrange the initial setup so that there are 3 minimums more or less symmetrically located on the sensor as shown in Figure 9. MCC is allowed to move left or right 80 units about the central 250 location. When the subroutine DISPL2 is called, it starts with the location MCO which is the location of the central minimum from the previous load increment. It then searches within ± 20 units of MCO for the current MCC. It also searches within ± 20 units of MCC + MSPR (righthand spacing) for MRC or within ± 20 units of MCC + MSPl (lefthand spacing) for MLC depending upon whether the pattern is moving to the left or right. If the fringe motion is too great, an error will be returned.

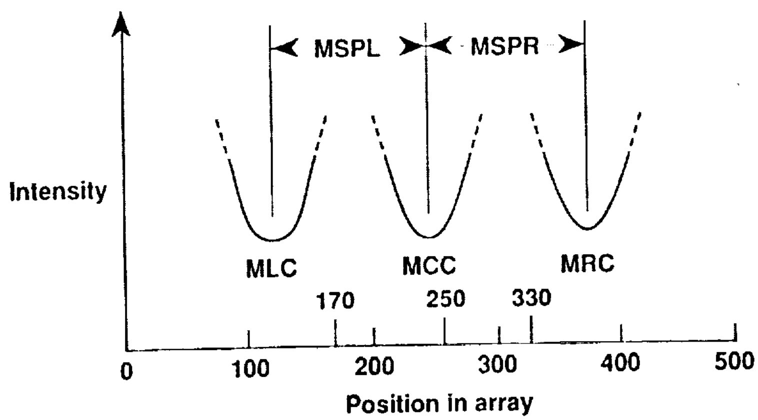


Figure 9. Diagram labelling the minimums (MLC, MCC, MRC) and spacings (MSPL, MSPR) of a fringe pattern signal. The central minimum, MCC, is initially positioned in the neighborhood of 250. If MCC moves out of the range 170 to 330, an adjacent fringe will have moved into that range and will be assigned the name MCC.

MCC is allowed to range 80 units to the left or right of 250 before it shifts to another minimum. For example, if MCC drops below 170, DISPL2 will relabel MRC as MCC and relabel the previous MCC as MLC. It can be seen from Figure 9 that the spacing between fringes, MSPL and MSPR, must be less than 150 (170 minus the 20 units for the search) or no minimum will be found for MLC or MRC when MCC reaches its limits. In practice, the initial spacing is set between 80 and 140 units.

DISPL2 returns a cumulative value, DISP, of the total displacement for each fringe pattern. It is calculated as follows for each channel:

1. DM = MCC - MCO, i.e. DM is the amount of shift of the central minimum between load increments, and it is in integers.

2. DM is then divided by the spacing, MSPL or MSPR depending upon whether MCC is on the right or on the left of 250, respectively; this is labelled DDM and is an incremental real value.

3. DDDM is the cumulative value and is updated at each increment by the statement 'DDDM1 = DDDM1 + DDM' (channel 1 for example).

4. Finally, DDDM is multiplied by the calibration factor, $\lambda/sin\alpha_o$ for the appropriate channel; this is called DISP.

The final strain is calculated in STRAIN2 as (DISP1 - DISP2)/2D0 where D0 is the gage length. It is multiplied by 1E06 to convert it to microstrain. The sign in the averaging equation depends on the orientation of the sensors. If they are symmetically oriented, the sign would be plus.

The start of the loading and measurement deserves some explanation. The load steps are incremented beginning with L = 0 (L = 0, NOS). DSPL2 actually runs twice for L = 0. The first time, MCO and the spacings found in the VIEW part of the program are used as the 'previous increment'. Since some time elapses between the running of VIEW and the running of STRAIN2 (because of final checks, setup of the plotter, etc.), it is necessary to reset the zero position. The second time DISPL2 runs for L = 0, it uses the MCO, MSPL, and MSPR obtained immediately before.

### *4.2.6 Subroutine MINC2*

Fringe minimums are found in DISPL2 by calling the subroutine MINC2 which is reproduced below. The strategy is to search around the minimum from the previous increment by computing the slope of the curve; when the slope becomes zero, the minimum has been found.

```
C ***************************************************************
      SUBROUTINE MINC2(AV,IBGN,ITMN,MC,IFERR)
C ***************************************************************
      INTEGER*2 AV(500),LHV,RHV,SLOPE
      IFERR=1
      DO 20 I=IBGN,ITMN,-1
      LHV=AV(I-4)+AV(I-3)+AV(I-2)+AV(I-1)
```

```
   RHV=AV(I+4)+AV(I+3)+AV(I+2)+AV(I+1)
   SLOPE=LHV-RHV
   IF (SLOPE .LE. 0.0) GO TO 20
   MC=I
   IFERR=0
   GO TO 30
20 CONTINUE
30 Return
END
```

IBGN and ITMN define the beginning and end of the search and are prescribed by DISPL2 for each minimum. IFERR is an error indicator that sends the program back to a printed error message in STRAIN2 if a minimum is not found. The program stops at that point and can possibly be continued if the cause was a glitch in the fringe signal. In practice, this error condition is fortunately rare.

One will note that MINC2 does some averaging also. This is certainly not necessary with high quality signals, but it may enable one to use the ISDG with poorer quality fringes.

### *4.2.7 Readout Programs -- ISDGSSR and ISDGR*

The final programs are ISDGSSR and ISDGR for reading the data from ISDGSS and ISDG and convering it from binary to ASCII format. They also permit one to plot the data on the color monitor.

## 5 Linear Diode Array System

Earlier versions of the ISDG used scanning mirrors that swept the fringe patterns past slit-covered photomultiplier tubes at a constant rate. Since the rate of sweep was constant and therefore proportional to the angle of the fringe pattern, the result was, in effect, a record of intensity versus angle. That approach is described in the following section. The newer linear diode array approach which is installed on the system in the Mechanics of Materials Branch at NASA-Langley is described in this section. Linear diode arrays are in current use at the Materials Laboratory of Wright Aeronautical Laboratories [5].

A main consideration in the use of photodiodes is the size of the aperture. The fringe photo in Figure 3b shows the speckle pattern that is always present when laser light reflects from surfaces. The speckle is generated by interference of the reflected rays because the surfaces cannot be perfect. So, the fringe pattern is not really very smooth upon close examination. If the apertures of the diodes are roughly the same size as the speckles, then the recorded intensity pattern will be very noisy. Earlier versions of linear diode arrays with apertures 25 $\mu$m square were examined in a study in 1975 [6] and discarded because of this problem.

Newer diode arrays have the same fine spacing, but a wider aperture. The arrays used are model RL0512S from E G & G Reticon of Sunnyvale, CA. Each array has 512 silicon photodiodes, each with a storage capacitor to integrate photocurrent and a multiplex switch for periodic readout. The aperture of each photodiode is 25 $\mu$m $\times$ 2.5 mm, and the length of the diode array is 12.6 mm. Figure 10 is a photograph of a diode array; it is packaged in a 16-pin chip. The array is mounted in a model RC1001 satellite board connected to a model RC 1000 mother board which powers the array and controls the scan.

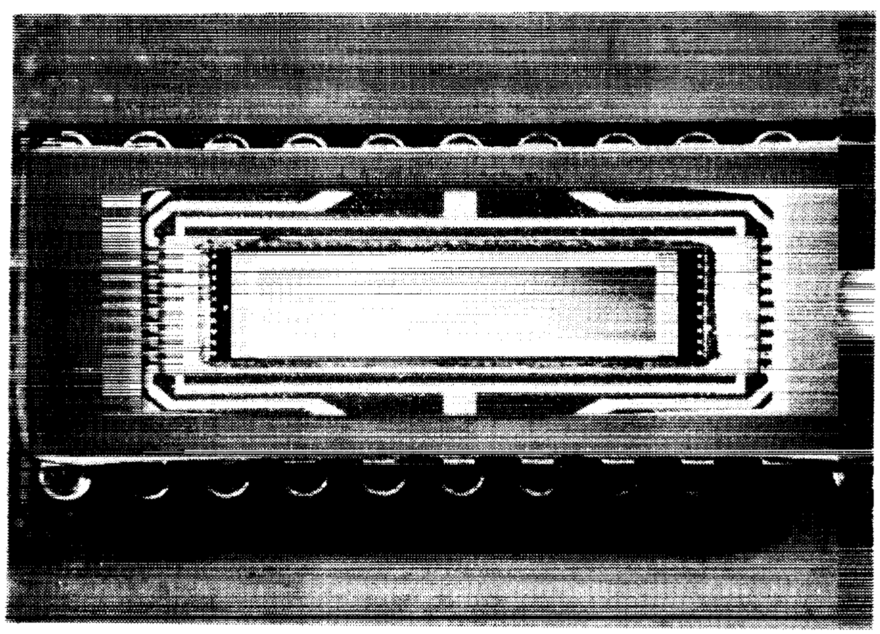

Figure 10. Macrophotograph of a linear diode array. the length of the active region is 12.5 mm, and the array is mounted in a 16-pin chip configuration.

The motherboard requires $\pm$ 15, + 5 volts. It has an on-board clock that can be used to vary the scanning rate, and it puts out a trigger signal at the end of each completed scan. It can also take an external clock and trigger. Since there are two channels, one motherboard is slaved to the other; this requires selecting jumper settings E2-E3 and E8-E9 on the slave board; the master board remains at settings E1-E2 and E7-E8. Figure 11 is a photograph of the two boards mounted in a chassis.

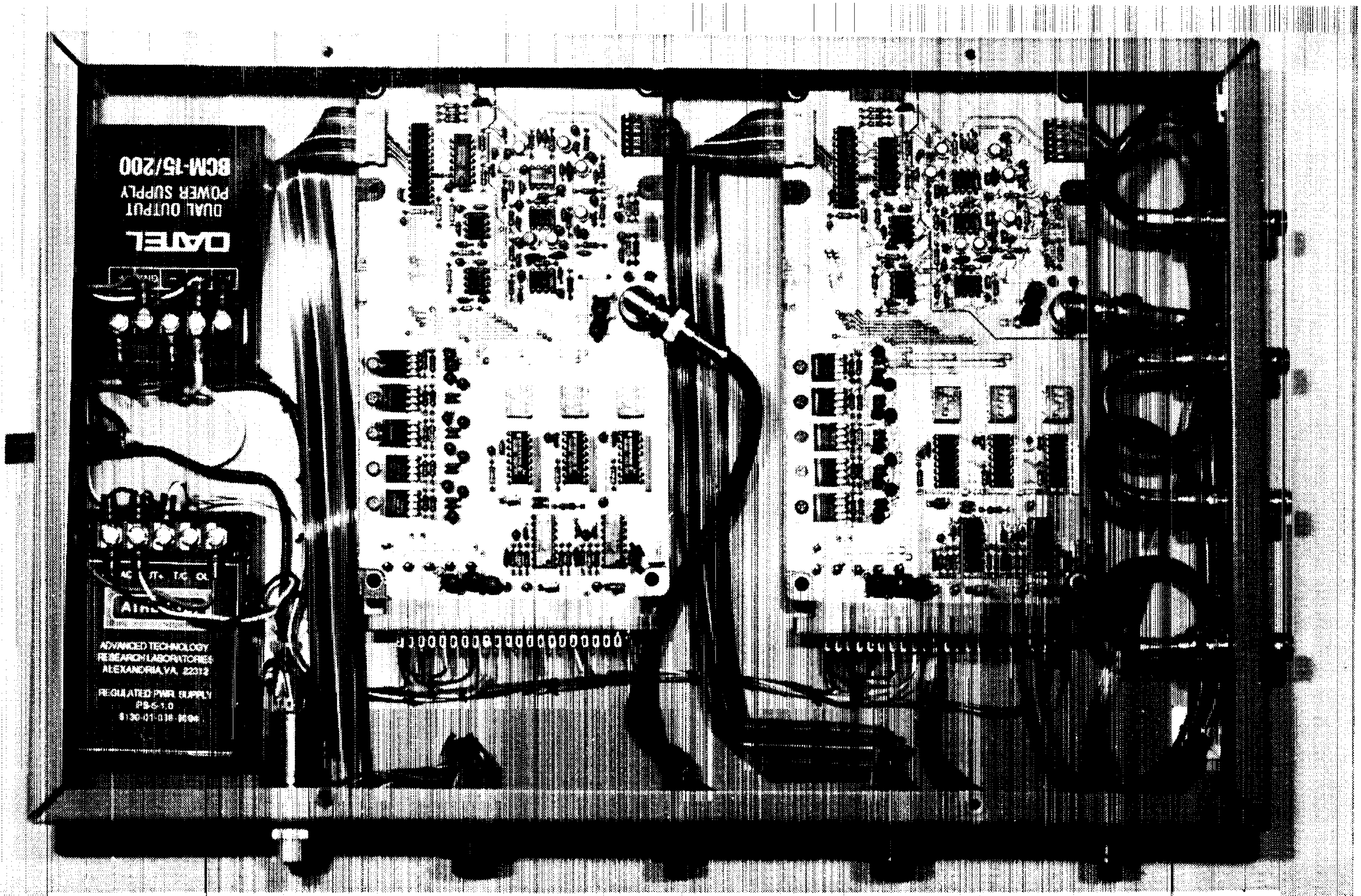

Figure 11. Photograph of the two motherboards that control the two linear diode arrays with their associated power supplies.



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The strategy is to control the microcomputer system from the master motherboard by using the Data Translation board in the external trigger mode. So, in the discussion of STRAIN2 above, the fringe data acquisition begins when the external trigger is sensed by the Data Translation board. Fringe data is taken at the rate specifed in the program setup; this rate must closely match twice the frequency of the master motherboard so that both channels can be sampled. However, it does not have to be precisely that value because the sample-and-hold of the A/D is long enough not to give spurious results if a sample is taken at the instant the output signal is switched from one photodiode to the next.

A more complete understanding of the timing can be gained from Figure 12 which is a timing diagram corresponding to a trigger frequency of 25 Hz — 40 milliseconds between trigger pulses. This means that the scanning frequency is 25 × 512 or 12.8 kHz. One would then set the frequency in ISDGSS or ISDG at 25.6 kHz. The first 40 ms are required for data acquisition which is initiated by the external trigger. The load increment for the succeeding measurement is then sent out so that the test machine will have maximum time to respond. It then takes approximately 30 ms for the computations; this can be slightly longer if the fringes move a lot and require longer searches. Finally, the displacement signal is sent out to the XY plotter (if used), and a 4 ms slack time is allowed.

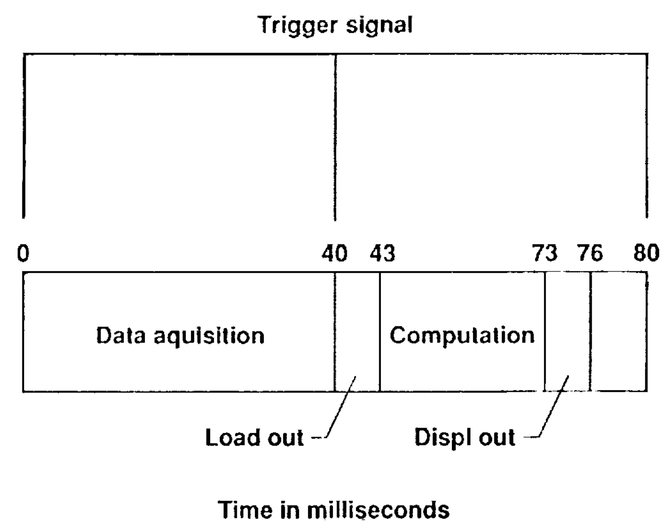


Figure 12. Timing diagram of single data point acquisition sequence. The trigger signal comes from the diode controller, and two 40 millisecond increments are required to acquire the data, compute and store the ISDG relative displacement, and increment the load signal to the test machine.

One sees from the diagram that approximately equal amounts of time are taken in data acquisition and in computation. This is an important consideration in terms of speeding up the system; one must work on both the sensor hardware and the software. Certainly computers with faster clocks are available, and one could speed up the scan of the linear diode array at the expense of the voltage output. It is quite reasonable to expect an improvement of 2 to 5 with few changes.

The TTL trigger signal from the motherboard is normally low with a high pulse that is 75 microseconds wide. The Data Translation board requires a trigger signal that is normally high and has a low pulse less than 1 microsecond wide. The inversion and compression is accomplished by a monostable multivibrator chip, 74123, connected as shown in Figure 13.

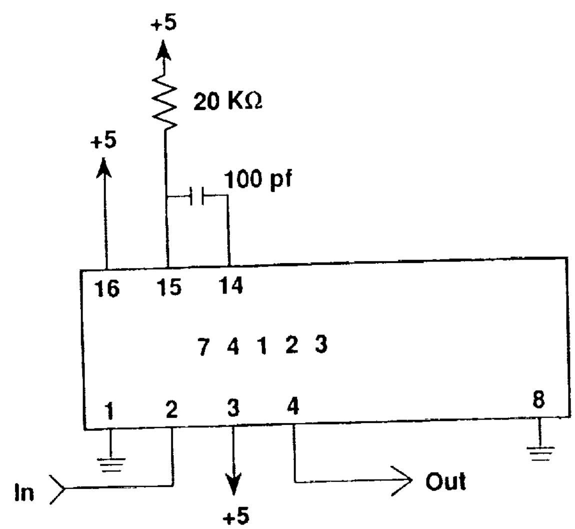


Figure 13. Wiring diagram for the trigger inverter circuit.

The fringe sensors and the associated optics can be attached to the test machine, but it is more convenient to mount them on a portable stand so that the ISDG can be used at different test stands. Figure 14 shows the laser, arrays, and optics mounted on an aluminum scanner board attached to a sturdy tripod. The tripod sits in front of a testing machine inside a cloth tent as shown in Figure 15. Vertical positioning can be accomplished with the post of the tripod which has a rack-and-pinion gear set and a locking screw. A milling table is attached to the post; this permits X-Y translation in a plane parallel to the floor as well as rotation about a vertical axis. This is a very handy attachment when it comes to final positioning of the front end of the scanner board relative to the specimen in the test machine.

The vertical optical plane of the scanner board is located 9 inches away from the board so that the fringes can be accessed by small front surface mirrors on steel posts sticking out from the board. Specimen grips are often large with a limited space between them so that the fringes cannot exit at the nominal 45 degree angle. The laser, in this

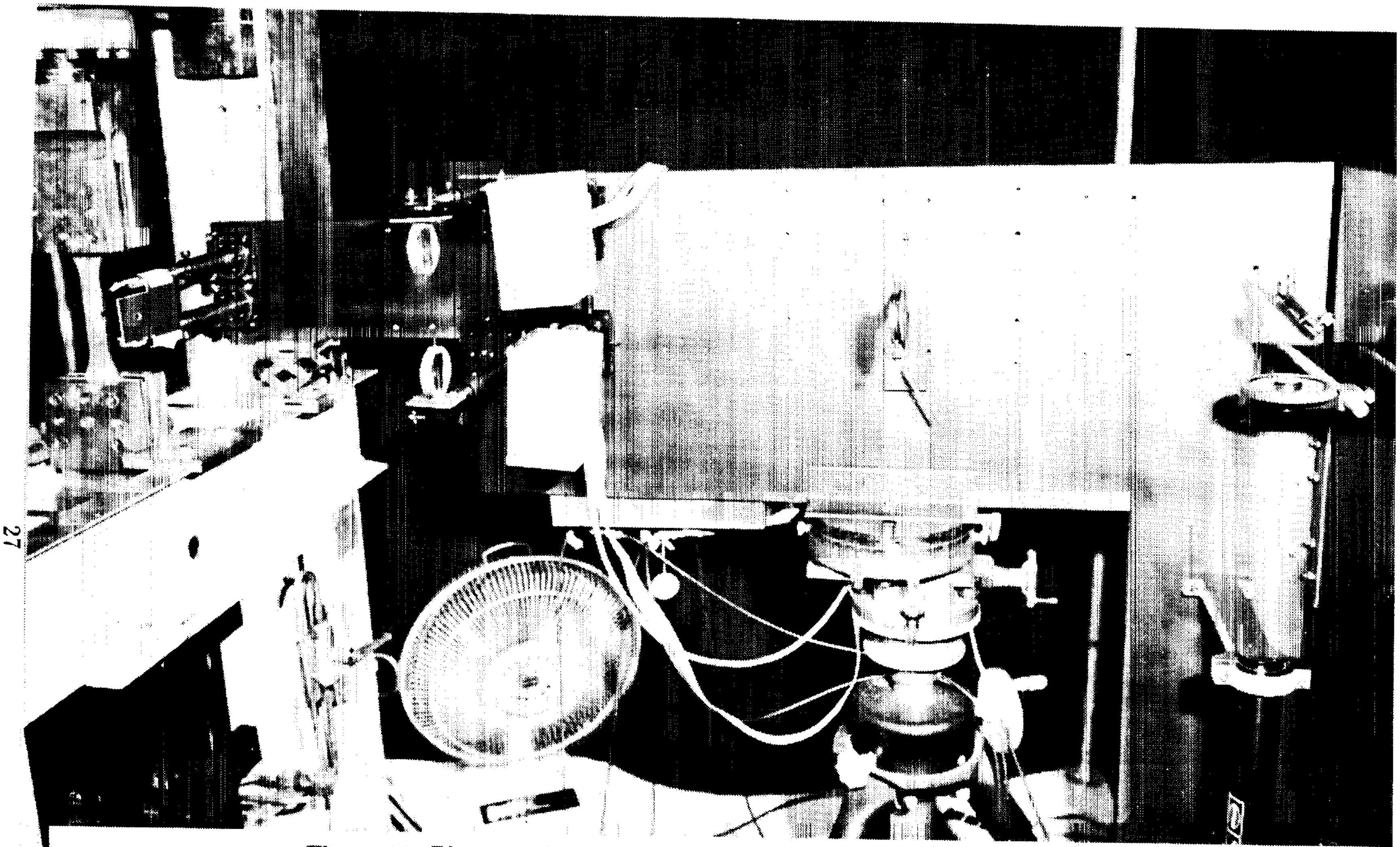

Figure 14. Photograph of the ISDG scanner board and optics in position at a test machine. Components are (from left to right): two fringe steering mirrors, two cylindrical lenses, two boxes containing the linear diode arrays, an incident beam focusing lens, a beam steering mirror, a variable neutral density filter, and the laser. The laser power supply and the electrical box containing the two motherboards are mounted on the back of the scanner board.

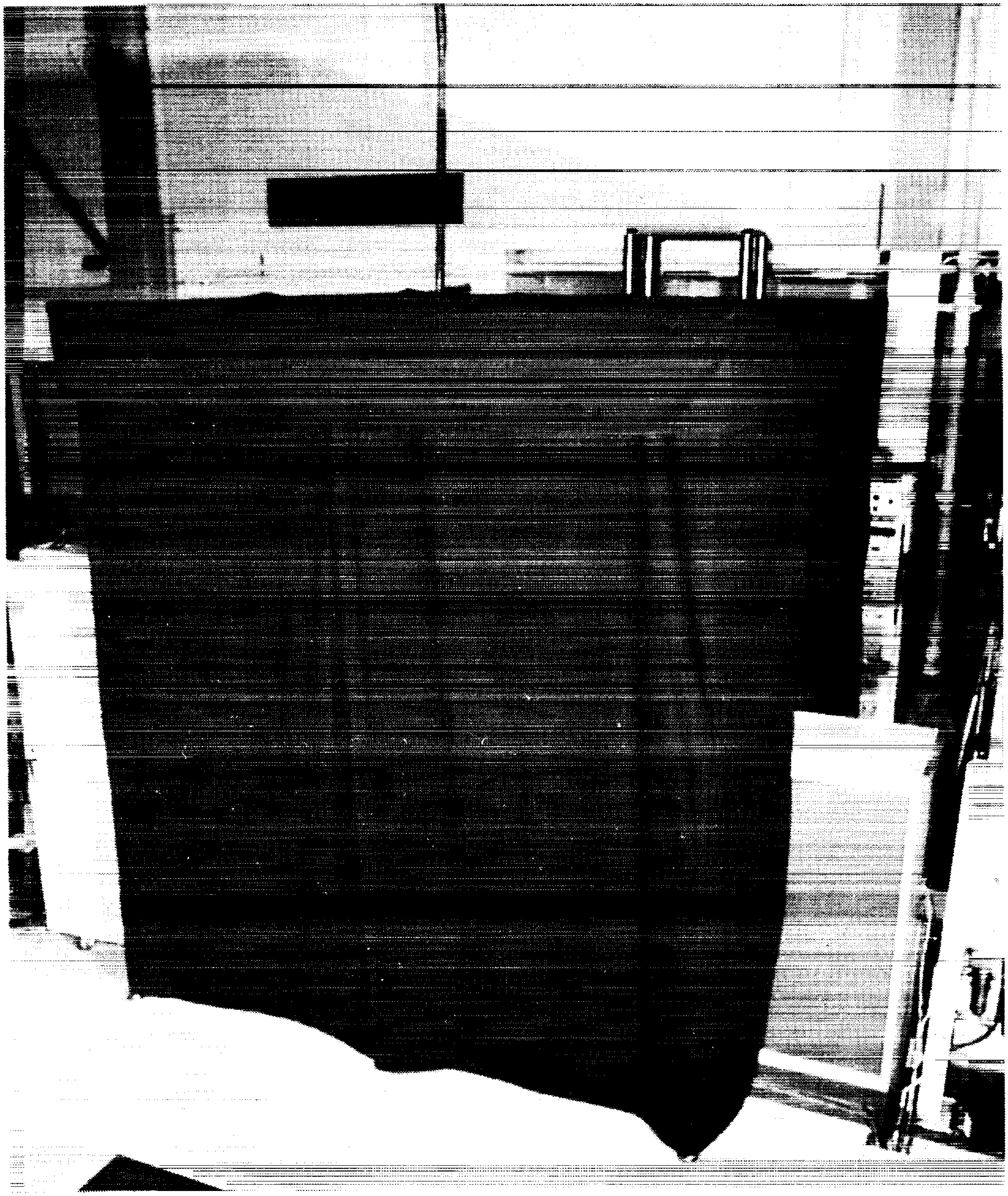

Figure 15. The black cloth tent covering the test machine and the ISDG scanner board. It is nine feet high and eight feet square.

case a 7 milliwatt He-Ne one with linear polarization (not required), is mounted 9 inches from the board and directed onto the specimen with a steering mirror. A focusing lens (which can be removed) is often needed to concentrate the laser beam on the indents — either for increased intensity or so that sets of indents that are close together can be accessed. This is a spherical lens with a 20 inch focal length; it can be positioned along the incident beam to change the spot size at the specimen. In some cases, it is desirable to concentrate the laser beam in only one dimension; in that case, a cylindrical lens with a long focal length could be used. The laser beam passes through a rotatable variable density filter (Ealing model 22-8981) which is useful for limiting the intensity at the specimen which can, with a focused beam, saturate the diode arrays.

The small mirrors that intercept the fringe patterns close to the specimen are simple front-surface mirrors with aluminum coatings; higher quality ones could be used to avoid the losses on reflection. They are mounted on steel rods attached to rotation stages to make it easy to direct the fringe patterns onto the arrays. Since the width of the array diodes is 0.1 inch and the width of the fringe pattern by the time it reaches an array is on the order of 1 inch, it is desirable to concentrate the pattern about a line perpendicular to the fringes with a cylindrical lens. This not only increases the intensity of the pattern on the array, but it demagnifies the speckles and smooths out the fringe pattern. The two cylindrical lenses have a 2 inch focal length and are mounted on both a beam-steerer stage and a translation stage (oriented horizontally) for ease of adjustment.

One should be cautioned about the use of any lens that compresses the fringes together, i.e. a spherical lens or a cylindrical lens with axis parallel to the fringes. As the specimen moves, the light rays shift on the lens resulting in a nonlinear shift at the array which would be difficult, if not impossible, to make symmetric for both patterns.

The diode arrays, with their satellite board are mounted in an electrical minibox attached to steel rods attached to a rotation stage and a translation stage (oriented vertically). It may in some cases be desirable to put interference filters in front of the arrays to screen out background light. The box containing the two motherboards and the laser power supply are mounted on the back side of the scanner board

The rotation stages, translation stages, and beam steerers are all from Newport Corporation and are models RSX-1, TSX-1A, and MM-2 respectively. The tripod, scanner board, and mounting stages comprise a mechanical system steady enough that there is little mechanical noise introduced into the signal. Note in Figure 14 that a small lab jack is mounted on the test machine to support the front of the scanner board.

A typical procedure for setting up the Scanner board goes as follows:

1. Position the tripod and board so that the optical axis appears to be at the right height and perpendicular to the specimen.

2. Remove the mirrors and adjust the laser beam onto the indentations. It is easier to work in a very dim area so that the fringes can be observed on a white card held

near the specimen. One must be careful with stray reflections that might enter the eye. Once the fringes are found, check the alignment of the scanner board to see that the laser beam is equally spaced between the mirror mounts and that it is perpendicular to the specimen. If the specimen is flat, one can observe the reflection from the surface; it should go back to the steering mirror.

3. Re-mount the mirrors and move the scanner board in or out as needed to cause the mirrors to intercept the fringe patterns.

4. Mount an optical shield to block out stray reflections from the specimen. This is a small piece of black cardboard with a hole for the incident laser beam. It is simply taped between the rods holding the mirrors.

5. Remove the cylindrical lenses and rotate the mirrors and adjust the diode boxes so that the center of the pattern falls on the arrays. At this point, turn on the diodes; it should be possible to see a good, but low-level signal on the oscilloscope. It may be necessary to move the arrays to various mounting positions on the board so that 3 to 4 fringes fall on the diode array.

6. Insert the cylindrical lenses and adjust them so that the compressed pattern covers the diodes. It may now be necessary to use the variable filter to bring the intensity down so that the output signal of the array falls within the 0 to 5 volt range.

7. Make a final adjustment of the steering mirror to center the pattern on the indents. One may want to center the beam slightly above or below the indents so that when the specimen is loaded, the indents have a greater range within the incident beam.

8. Translate or rotate each diode array so that the spacings of the two patterns are similar and the middle minimum is in the center of the scan.

Typical fringes are shown in Figure 16; these were taken with the PREVIEW program. One probably will not get fringe records that look any better than this; on the other hand, the ISDG can be used with fringes that are a lot worse as long as the minimums are well-defined.

## 6 Scanning Mirror System

The scanning mirror system at Johns Hopkins University that is used for measuring fringe intensities is shown in Figure 17. Instead of one linear diode array for each channel, there is a scanning mirror and photomultiplier tube (PMT) for each channel. These are mounted on a scanner board that is attached to the testing machine in this particular case. The laser, steering mirror, and optical shield are attached to the scanner board as in the array system.

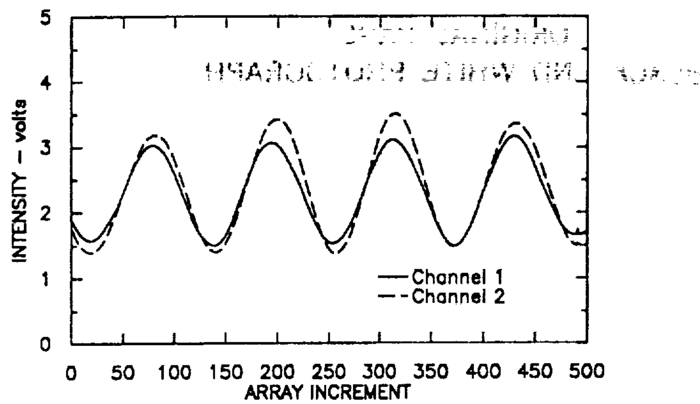


Figure 16. Typical fringe intensities as recorded by the PREVIEW program.

The operation of the sensors is controlled by an external function generator that puts out a periodic linear sawtooth voltage signal to the mirrors and a trigger signal to the computer at the beginning of each period. The trigger signal controls the microcomputer in the same fashion as it does for the diode system, and its period is typically 90 milliseconds. The linear sawtooth causes the fringes to sweep past the PMT at a constant rate. Each PMT has a narrow slit aperture so that the voltage output from the PMT is proportional to the intensity of the fringe pattern. The fringe data is taken in a burst mode by the microcomputer upon command from the trigger signal. The timing is such that the fringe data is taken in the first 40 milliseconds of the scan and the calculations and data storage are accomplished in the last 50 milliseconds.

The photomultiplier tubes are RCA type 4840 and are powered by RCA PF-1042 power modules that require 13.5 volts input. The PMTs have a large side-looking aperture, a high dark current, and are inexpensive.

The scanning mirrors are model G120DT from General Scanning, Inc. of Watertown, MA with a frequency response of about 600 Hz. These are torsional shaft scanners, i.e. one end of the small shaft is fixed, and the shaft is twisted by the electromagnetic field in a coil surrounding a magnetic core attached to the shaft. A small, 7 mm by 16mm by 1 mm, mirror is attached to the other end of the shaft. A capacitance-based angular transducer is also mounted on the shaft and provides the feedback signal for control of the angular motion of the mirror. A model CX-660 control module is required for each scanning mirror; it accepts a $\pm$ 10 volt signal and provides easy adjustment of both the magnitude and the mean position of the scan. It is therefore very easy to adjust the scans so that the proper number of fringes are sampled during the initial part of the linear sweep. A typical sweep is approximately one degree.

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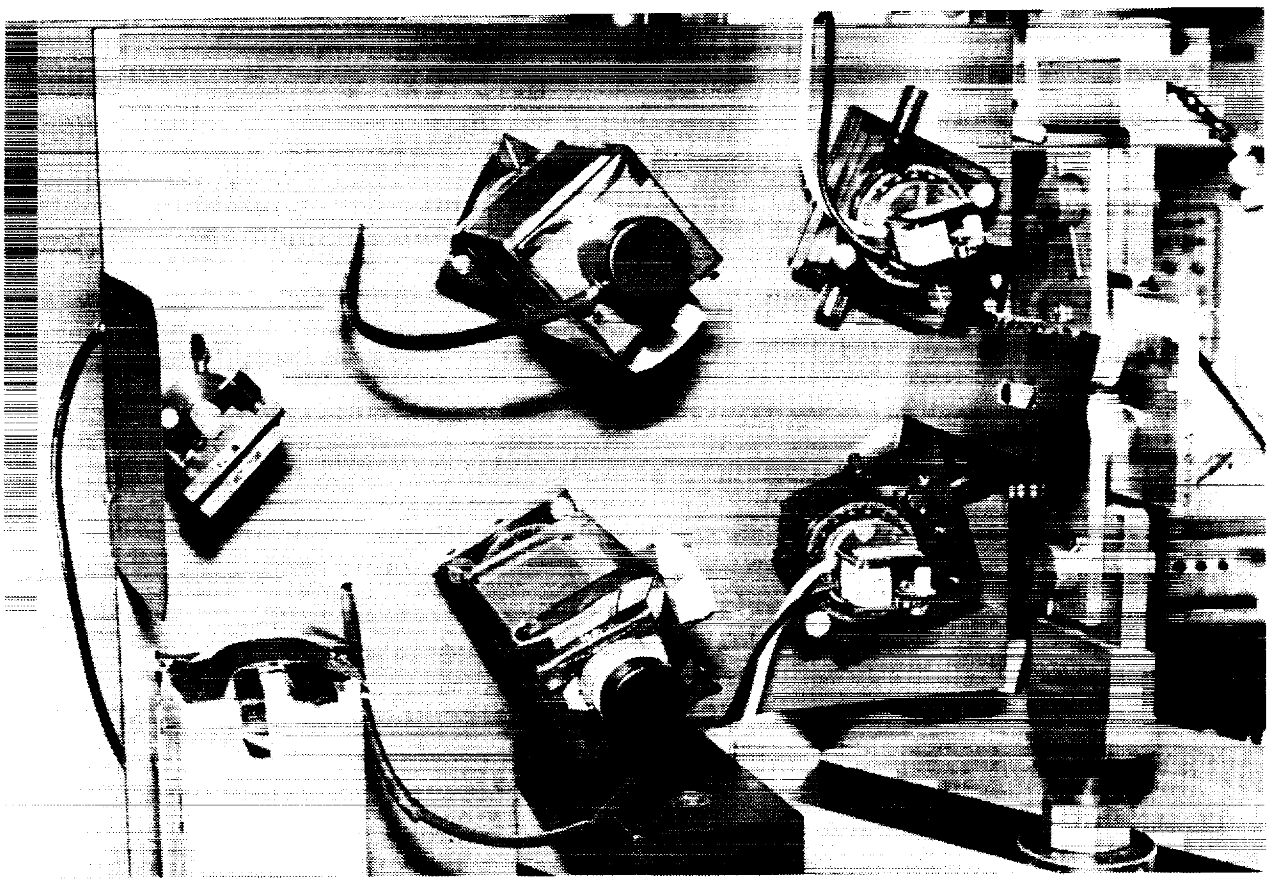

Figure 17. Photograph of the scanning mirror system at Johns Hopkins University. Two scanning mirrors, two photomultiplier tubes, and the laser are mounted on an aluminum plate attached to the testing machine.

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The programs for running a test are very similar to those used for the linear diode arrays except that PREVIEW is not used. It is very easy to adjust the positon and spacing of the fringe pattern, and this is done while monitoring the fringes on an oscilloscope in the initial setup. The VIEW routine within ISDG or ISDGSS always starts looking for the minimums in the same places, so PREVIEW is not needed. The only other difference is that 256 data points are taken per fringe pattern instead of 512. There is no special reason for this; it is a holdover from early development of the ISDG when programming was done in assembly language.

# 7 Examples of Measurements

A review paper describing applications of the ISDG up to that time was published in 1983 [1]. More uses of the technique have been made by various people since then, but that report does give an overview of testing situations where the ISDG might be useful — including dynamic and high-temperature measurements. The purpose of this section is to present a few typical examples of data taken both with the ISDG system in place at NASA-Langley and the biaxial system at Hopkins.

## *7.1 Elastic Strains at a Notch Root*

The results presented here are from a single-notched specimen of 4340 steel. It was 25.5 mm wide by 5.2 mm thick with a 3.18 mm radius semicircular notch; the notch root was electropolished before testing. Indentations were placed 150 $\mu$m apart at five positions across the root of the notch. One set was placed at 200 $\mu$m from each edge, and two more sets were placed at the quarter points. It was intended that a set be placed at the center of the specimen, but there was a blemish in the surface so the 'center' indents are actually 150 $\mu$m off-center. A bright curved surface will reflect the laser beam back into the diode arrays, so the area near the indents was masked with 1 mm wide black tape (the kind used by draftsmen to tape lines on posters). This is fairly easy to apply using a stereo microscope and tweezers.

Figure 18 shows the results from measurements at the five locations — taken sequentially of course. Note that the last four plots have been shifted along the horizontal axis. Three of the plots are very straight, but two are curved. The surface at the notch root is smooth, but not necessarily perfectly cylindrical (perhaps because of the electropolish), and this may account for the differences. The data shows little hysteresis upon unloading. If one compares the slopes of the 'right edge' and the 'center' plots, one sees a smaller slope at the center — indicating more strain and consequentially a higher effective stress concentration factor. These plots show the effect of constraint across the notch root even though it is small in a specimen this thin. It is interesting to note that the data from the center plot shows an elastic stress concentration factor of 3.37 compared with values predicted from a two-dimensional boundary force analysis of 3.42 (uniform stress boundary condition) and 3.30 (uniform displacement boundary condition).

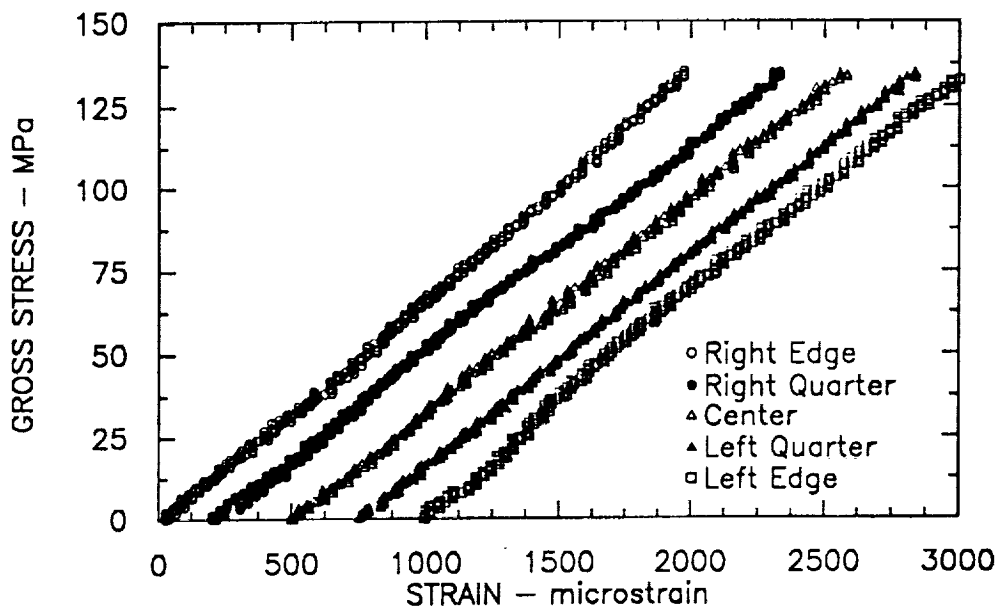


Figure 18. Plots of elastic strains at five positions across a semicircular notch in a 5 mm wide steel specimen.

Figure 19 is an expanded plot from one of the data sets of Figure 18. It shows the scatter of the data about a least-squares straight line which is shown for convenience. It appears that there is a lot of scatter in the load signal, but the scatter really comes from the fact that the ISDG has a finite least-count resolution which corresponds to a shift of the center minimum on one channel by one positon in the data array. All of the data in Figure 19 lie on vertical lines that are approximately 14 microstrain apart in this case. The least-count resolution is therefore 14 microstrain.

Figure 19 also shows that the ISDG, while not really suited for small elastic strain measurements, could be used for measurements over short gage lengths. It is common in elastic testing to repeat the tests, so one could run several ISDG measurements, average them, and smooth out the results. The ISDG has a 'resolution' here of 14 microstrain over a gage length of 150 $\mu$m , whereas the smallest foil gage has a resolution of 1 microstrain over a gage length of 380 $\mu$m (0.015 inches). But, the foil gage with its tabs covers a much larger area.

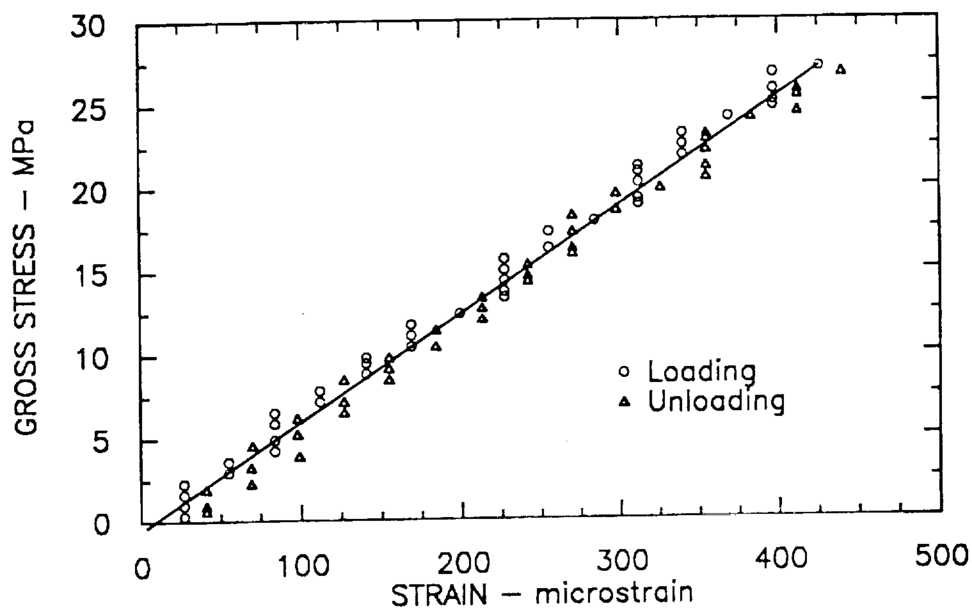


Figure 19. An expanded plot of the 'right edge' data from Figure 18.

### 7.2 *Elastoplastic Strain at a Notch Root*

The same steel specimen that was used above was loaded until plastic yielding occurred at the notch root. The center set of indentations were monitored. Figure 20 shows the results and some of the problems associated with ISDG testing when large loads are involved (the maximum load here was approximately 84,500 N corresponding to 655 MPa). The plot consists of three segments correponding to three separate loadings, and the strains were shifted in the last two segments to correspond to the last strain of the previous segment.

First, it was not possible to load the specimen to yielding in one test because the indents moved out of the laser beam. The focussing lens was used to concentrate the laser beam so that the neighboring indentations did not interfere, and this limited the permissible motion of the indents. The amount of allowable vertical motion could have been increased by using a cylindrical lens to concentrate the beam only in the horizontal direction. Actually, this was not a problem with this specimen; it was intended to load once over the range 0 to 345 MPa where the behavior was known to be elastic and then a second time over the range 345 MPa to 690 MPa.

The first segment of loading went as planned with good results. The specimen slipped in the grips in the second segment at approximately 565 MPa; the ISDGSS program shut down when the fringe patterns were lost. The test machine controller must then be brought back to zero load with the OFFSET dial on the controller and shut down before the load input cable is disconnected. Slippage in the grips is an avoidable problem, but it is more critical when the ISDG is used.

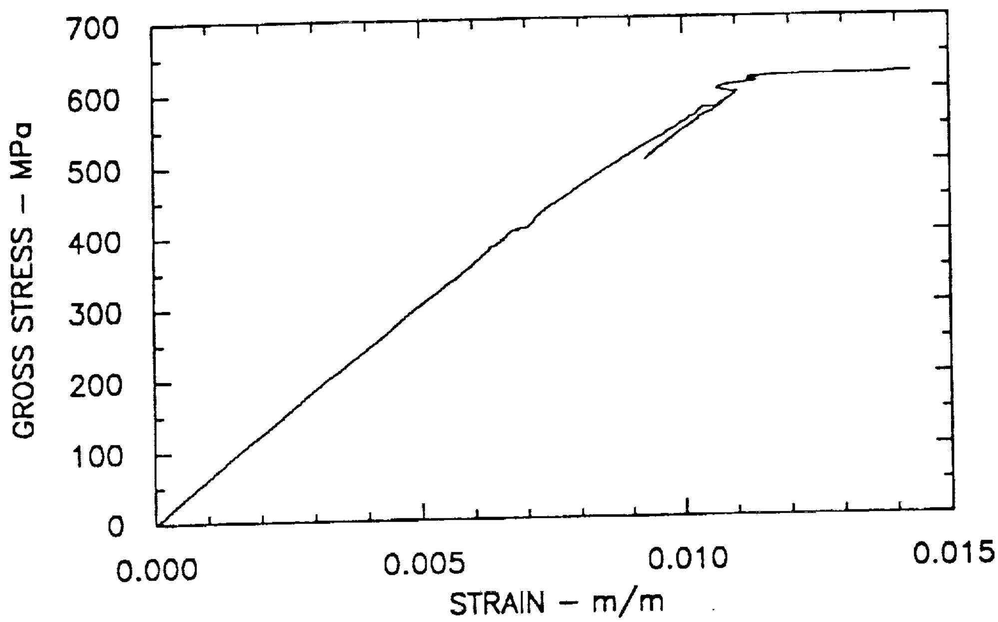


Figure 20. Elastoplastic notch root strain from a 4340 steel specimen with a 3.18 mm radius semicircular notch.

The third segment of Figure 20 was obtained by restarting the test over a range of 517 MPa to 690 MPa. One can see the effect of unloading from the second test, and plastic yielding occurred soon after the previous maximum load had been exceeded. The irregularity of the strain signal at the instance of yielding is perhaps associated with the short gage length of the ISDG. This version of 4340 steel had a high yield stress with a slightly higher ultimate stress, so the stress-strain curve is nearly horizontal in the plastic region. This third segment shut down when the ISDG strain changed too much for the program to follow.

The results in Figure 20 are from the first test using the ISDG in that load frame; there had also been no experience with testing 4340 steel. One gains by experience, as is shown in the following section.

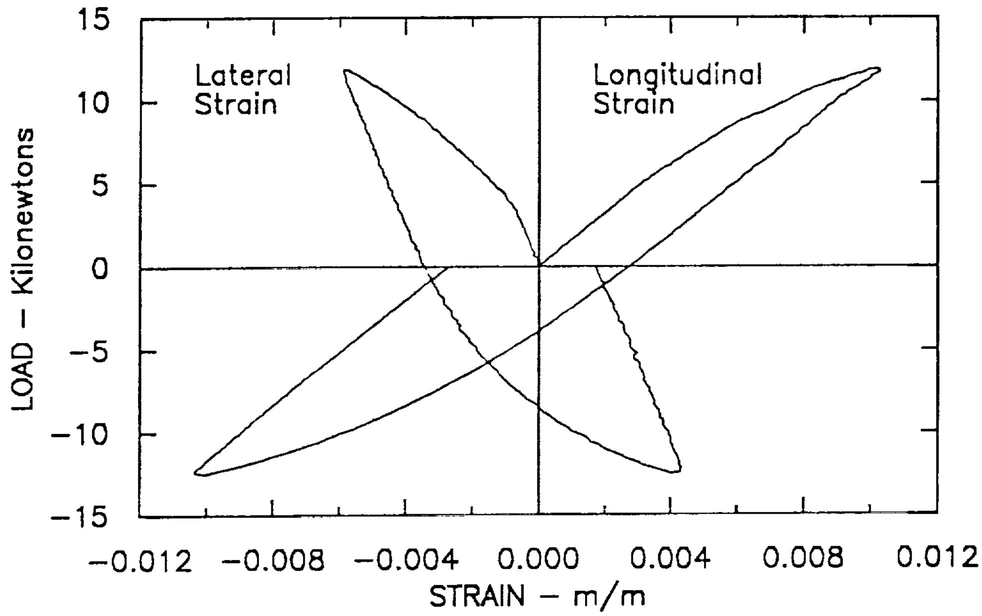


Figure 21. Biaxial strains at a notch root in an aluminum specimen as measured with the system at Johns Hopkins.

### 7.3 *Biaxial Notch Strains*

Figure 21 shows the results of longitudinal (positive) and lateral (negative) strain measurements at a notch root using the system at Hopkins. The specimens were of 2024-T351 aluminum, and were double-notched with notches having a 4.76 mm radius. It should be noted that this test was run in one segment with no problems of the indentations moving out of the laser beam. The specimens were only 2.54 mm thick, so the loads were smaller, and the grips are very sturdy (a slight preload is applied before they are finally tightened). The yielding of the material is less abrupt which makes it easier for the ISDG to follow the plastic deformation. Also, the fact that considerable experience has been built up with that particular system should not be ignored.

### 7.4 *Crack Opening Displacement*

A single-notched 4340 steel specimen (same geometry as in Section 7.1) was cyclicly loaded until a fatigue crack appeared at the notch root; it was allowed to grow until it was 500 $\mu$m long. The crack was not at the very bottom of the notch; apparently it initiated at some inclusion rather than at the highest stress (this was an unusual occurrence). The specimen was then removed and indentations applied across the center of the crack. The indents were 120 $\mu$m apart, and one of them did not look very good because of the rumpled surface at the notch root. Nevertheless, the fringe patterns were adequate, and load-displacement records taken.

Figure 22 is the load-displacement plot. It was also taken in three segments (-33.4 kN to -11.1 kN, -11.1 to +11.1, and +11.1 to +33.4) although it could have been done in two. This shows the ISDG at its best measuring small displacements over short gage lengths with high resolution. Note that this is a loading-unloading test. The significant features of the plot are the linear portion at negative loads which actually correspond to the strain in the specimen, the nonlinear region around zero load which identifies the opening load, and the upper linear region whose slope can be used to estimate the crack length.

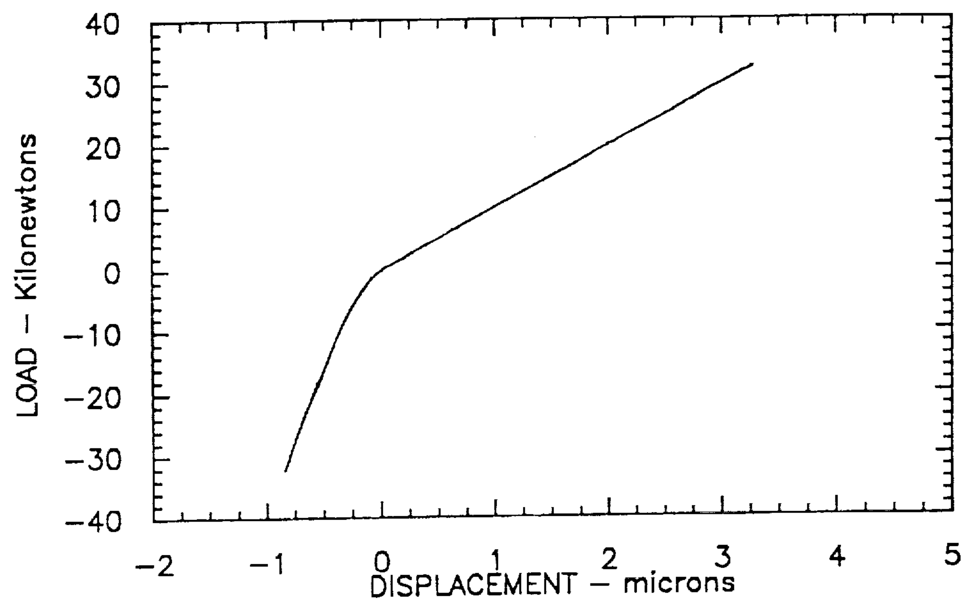


Figure 22. Crack opening displacement across a fatigue crack at a notch root.

## 8 Closing Remarks

It is hoped that the ISDG has been adequately described above so that one could construct a system to meet specific needs. One finds that once the ISDG is set up for a particular application, its operation becomes routine. However, the intial setup and learning process requires patience.

Either version of the sensors is satisfactory. The diode arrays are cheaper and guarantee that there is no drift of the fringe positions with time. If the fringes are dim because of small indentations or a degraded surface, the scanning mirrors with the PMTs will work better. The scanning mirror system is easier to adjust, but one could make a more elaborate mounting arrangement for the arrays.

The ISDG can be speeded up with faster sensors and computers. Resonant scanning mirrors, which oscillate at a higher frequency, or rotating mirrors could be used to sweep the patterns past the PMTs at a faster rate. Microcomputers running at a faster clock rate and an optimized program (the one described is by no means optimal) could speed up the measurements.

A major drawback to the ISDG is rigid body motion; this limits it to simple geometries. In principle, one should be able to monitor the four diffracted patterns to ascertain the movement of the indents. Or, some other motion-measurement device could be used so that one could correct for the motion. Although complicated, the additional efforts would greatly expand the capabilities of the ISDG.

# 9 Acknowledgements

A grant from NASA Langley in 1974 enabled development of the first computer-based ISDG, and the system described herein is a direct descendant of that effort [6]. The foresight of Dr. W. Elber in encouraging that initial work is quite evident some 15 years later.

The author appreciates the support of the National Research Council for a six-month Senior Associateship at NASA Langley. The support of the Mechanics of Materials Branch, in particular the encouragement of Dr. J. C. Newman and Dr. C. E. Harris is gratefully acknowledged. Finally, the excellent professional cooperation of the laboratory technicians, in particular Mr. Mike Bell, is recognized.

## References


[1] Sharpe, W.N., Jr., "Applications of the Interferometric Strain /Displacement Gage", *Optical Engineering*, Vol. 21, pp. 483-488, (1982).

[2] Jenkins, F. A. and White, H. E., FUNDAMENTALS OF OPTICS, McGraw-Hill Book Company, 1957.

[3] Sharpe, W. N., Jr. and Wang, K. C., "Small Attachable Interferometric Strain Gages", *Experimental Mechanics*, Vol. 28, pp. 136-141, (1988).

[4] Sharpe, W. N., Jr., "Preliminary Development of an Interferometric Strain Gage for Use on Nosetip Materials Subjected to Thermal Shock", AFML-TR-76-63, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, (1976).

[5] G. Hartman and T. Nicholas, "An Enhanced Laser Interferometer for Precise Displacement Measurements", *Experimental Techniques* , Vol. 11, pp. 24-26, (1987).

[6] Sharpe, W. N., Jr., "Development and Application of an Interferometric System for Measuring Crack Displacements", Final Report NASA-CR-145106, 77N12367, (1977).

# Appendix

```
C ******************** PREVIEW ********************************
C       W.N. SHARPE, JR JUNE 13, 1989
C
C THIS IS A PROGRAM TO ACQUIRE THE DATA FROM TWO FRINGE CHANNELS
C AND STORE AND/OR PLOT IT.
C LINK WITH ATLFOR AND GRAFEX33/SE:1024 LIBRARY FILES

$STORAGE:2
$INCLUDE:'ATLDEFS.FOR'
$INCLUDE:'ATLERRS.FOR'
$DEBUG
C-------SET ARRAYS, SPECIFICATIONS
        CHARACTER*10 xlegend
        CHARACTER*10 ylegend
        CHARACTER*8 char
        CHARACTER IN
        CHARACTER*10 FILENAME
        INTEGER*2 SCANCOUNT,RLB,BUF1(1024),NOB1
        INTEGER*2 ADCHANNELS(16),ADGAINS(16)
        INTEGER*4 BL
        INTEGER*2 BV1(500),BV2(500)
        DIMENSION AV1(500),AV2(500),AK(500)
        DIMENSION AM1(6),AM2(6),AAV1(6),AAV2(6)
        REAL*4 RATE

5       CONTINUE

C-------SETUP FOR DATA ACQUISITION
        STATUS = ALINIT()
        STATUS = ALSB(1)
        STATUS = ALRSET()
        SCANCOUNT=2
        ADCHANNELS(1)=1
        ADCHANNELS(2)=2
        ADGAINS(1)=1
        ADGAINS(2)=1
        STATUS=ALSETA(2,SCANCOUNT,ADCHANNELS,ADGAINS)

C-------SET GRAPHIC MODE FOR EGA CARD
        mode=16
        call QSMODE(mode)
        call QCMOV(0,6)

C-------GET DATA
        WRITE(*,*) ' ENTER SAMPLING RATE...'
        READ(*,*) RATE
        RATE=RATE*1E3
        STATUS=ALSF(RATE)
        STATUS=ALST(NINT(4*1024/RATE))
        STATUS=ALFDL(buf1(1),bl)
        STATUS=ALDB(nob1,buf1(1),1024)
        STATUS=ALLB(nob1)
        STATUS=ALBAD()
        STATUS=ALRELB(1,RLB)
        STATUS=ALRETB(RLB)
        STATUS=ALSTOP()
        WRITE(*,*) 'RELEASED BUFFER #',RLB

C-------AVERAGE RAW DATA
        WRITE(*,*) 'NUMBER OF POINTS TO AVERAGE; 1 or 10? '
```

```
        READ(*,*) NP
        IF(NP.EQ.1) GOTO 195
        IF(NP.EQ.10)GOTO 400
195       DO 200 K=1,500
           BV1(K)=BUF1(2*K+7)
           BV2(K)=BUF1(2*K+8)
200       CONTINUE
        GOTO 500
400       DO 450 K=1,490
           BV1(K)=(BUF1(2*K+7)+BUF1(2*K+9)+BUF1(2*K+11)+BUF1(2*K+13)
     *     +BUF1(2*K+15)+BUF1(2*K+17)+BUF1(2*K+19)+BUF1(2*K+21)
     *     +BUF1(2*K+23)+BUF1(2*K+25))/10
           BV2(K)=(BUF1(2*K+8)+BUF1(2*K+10)+BUF1(2*K+12)+BUF1(2*K+14)
     *     +BUF1(2*K+16)+BUF1(2*K+18)+BUF1(2*K+20)+BUF1(2*K+22)
     *     +BUF1(2*K+24)+BUF1(2*K+26))/10
450       CONTINUE
        GOTO 500
500     CONTINUE

C-------SEPARATE INTO ARRAYS; PLOT ROUTINE NEEDS TO START AT 1
          DO 210 K=1,500
           AV1(K)=(BV1(K)-2048)/204.8
           AV2(K)=(BV2(K)-2048)/204.8
           AK(K)=K
 210      CONTINUE

C-------SAVE DATA IF WISH
        WRITE(*,*) 'SAVE DATA ?  Y ?'
        READ(*,'(A1)') IN
        IF (IN.NE.'Y') GOTO 550
        WRITE(*,*) ' NAME OF DATA FILE'
        READ(*,'(A10)') FILENAME
        OPEN(1,FILE=FILENAME,STATUS='NEW',ACCESS='SEQUENTIAL',
     *  FORM='FORMATTED')
          DO 99 J=1,500
   99      WRITE(1,98) J,AV1(J),AV2(J)
   98      FORMAT(1X,I3,3X,F7.3,3X,F7.3)
        CLOSE(1)

C-------FIND MINIMUMS
C       LINES 26 AND 52 SET THE SIGN AT -1, NOT 0, TO TAKE CARE OF
C       THE RARE INSTANCE WHEN AV1(K+2)-AV1(K) IS ZERO WHICH
C       INCREMENTS KTCR TWICE.

550     CONTINUE
        IS = 8

C-------FIND MINIMUMS FOR CHANNEL 1
        IF (AV1(6) - AV1(1)) 21,22,23
 21     ISGNO = -1
        GOTO 24
 22     ISGNO = 0
        GOTO 24
 23     ISGNO = 1
 24     KTCR = 0
      DO 40 K = 2,490
        IF (AV1(K+IS) - AV1(K)) 25,26,27
 25     ISGN = -1
        GOTO 28
 26     ISGN = -1
```

```
        GOTO 28
 27     ISGN = 1
 28     IF (ISGN - ISGNO) 39,39,29
 29     KTCR = KTCR + 1
        IF (KTCR - 2) 30,31,32
 30     AM1(1) = K
        AAV1(1) = AV1(K)
        GOTO 39
 31     AM1(2) = K
        AAV1(2) = AV1(K)
        GOTO 39
 32     IF (KTCR - 4) 33,34,35
 33     AM1(3) = K
        AAV1(3) = AV1(K)
        GOTO 39
 34     AM1(4) = K
        AAV1(4) = AV1(K)
        GOTO 39
 35     IF (KTCR - 6) 36,37,39
 36     AM1(5) = K
        AAV1(5) = AV1(K)
        GOTO 39
 37     AM1(6) = K
        AAV1(6) = AV1(K)
        GOTO 39
 39     ISGNO = ISGN
 40   CONTINUE

C-------FIND MINIMUMS FOR CHANNEL 2
        IF (AV2(6) - AV2(1)) 51,52,53
 51     ISGNO = -1
        GOTO 54
 52     ISGNO = -1
        GOTO 54
 53     ISGNO = 1
 54     KTCR = 0
      DO 70 K = 2,490
        IF (AV2(K+IS) - AV2(K)) 55,-
 55     ISGN = -1
        GOTO 58
 56     ISGN = -1
        GOTO 58
 57     ISGN = 1
 58     IF (ISGN - ISGNO) 69,69,59
 59     KTCR = KTCR + 1
        IF (KTCR - 2) 60,61,62
 60     AM2(1) = K
        AAV2(1) = AV2(K)
        GOTO 69
 61     AM2(2) = K
        AAV2(2) = AV2(K)
        GOTO 69
 62     IF (KTCR - 4) 63,64,65
 63     AM2(3) = K
        AAV2(3) = AV2(K)
        GOTO 69
 64     AM2(4) = K
        AAV2(4) = AV2(K)
        GOTO 69
 65     IF (KTCR - 6) 66,67,69
```

```
 66      AM2(5) = K
         AAV2(5) = AV2(K)
         GOTO 69
 67      AM2(6) = K
         AAV2(6) = AV2(K)
         GOTO 69
 69      ISGNO = ISGN
 70    CONTINUE

C-------SET PLOT PARAMETERS
        jcol1=100
        jcol2=600
        jrow1=160
        jrow2=340
        xmin=0.
        xmax=500.
        ymin=-1.
        ymax=5.
        xorg=0.
        yorg=-1.0
        iopt=0
        yoverx=0.012
        aspect=1.0
        call QPLOT(jcol1,jcol2,jrow1,jrow2,xmin,xmax,ymin,ymax,xorg,yorg
     *            ,iopt,yoverx,aspect)
C------SET AXIS PARAMETERS
        xst=0.
        xfin=500.
        yst=-1.0
        yfin=5.0
        xmajor=100.
        ymajor=1.
        minor=1
        minor=1
        label=1
        ndecx=0
        ndecy=0
        call QXAXIS(xst,xfin,xmajor,minor,label,ndecx)
        call QYAXIS(yst,yfin,ymajor,minor,label,ndecy)
C---------CONVERT LOCATIONS TO PIXELS
        call QRTOI(xst,yst,ist,jst)
        call QRTOI(xfin,yfin,ifin,jfin)
C---------DRAW BOX
        kolor=2
        call QLINE(ist,jfin,ifin,jfin,kolor)
        call QLINE(ifin,jfin,ifin,jst,kolor)
        call QLINE(ifin,jst,ist,jst,kolor)
        call QLINE(ist,jst,ist,jfin,kolor)
C------SET AXIS LEGENDS
           nxlc=10
           xlegend='INCREMENT'
           jcol=310
           jrow=120
           iorien=0
        call QGTXT(nxlc,xlegend,kolor,jcol,jrow,iorien)
           nylc=10
           ylegend='VOLTAGE'
           jcol=40
           jrow=300
           iorien=-1
```

```
      call QGTXT(nylc,ylegend,kolor,jcol,jrow,iorien)
C------SET PLOT PARAMETERS
      ndots=0
      lkolor=6
      isymbl=-2
      klrsym=6
      call QSETUP(ndots,lkolor,isymbl,klrsym)
C------PLOT DATA FROM FIRST ARRAYS; THEY MUST BE REAL
      itype = 1
      npt=500
      call  QTABL(itype,npt,AK,AV1)
C------SET PLOT PARAMETERS
      ndots=0
      lkolor=3
      isymbl=-2
      klrsym=6
      call QSETUP(ndots,lkolor,isymbl,klrsym)
C------PLOT DATA FROM SECOND ARRAYS; THEY MUST BE REAL
      itype = 1
      npt=500
      call  QTABL(itype,npt,AK,AV2)
C------PLOT MIMIMA FROM FIRST ARRAYS; THEY MUST BE REAL
      ndots=0
      lkolor=6
      isymbl=4
      klrsym=4
      call QSETUP(ndots,lkolor,isymbl,klrsym)
      itype = 0
      npt=6
      call  QTABL(itype,npt,AM1,AAV1)
C------PLOT MIMIMA FROM SECOND ARRAYS; THEY MUST BE REAL
      ndots=0
      lkolor=6
      isymbl=7
      klrsym=4
      call QSETUP(ndots,lkolor,isymbl,klrsym)
      itype = 0
      npt=6
      call  QTABL(itype,npt,AM2,AAV2)
C-----POSITION CURSOR
      call QCMOV(0,6)
     WRITE(*,41)
 41  FORMAT(10X,'M11',7X,'M12',7X,'M13',7X,'M14',7X,'M15',7X,'M16')
     WRITE(*,42) AM1(1),AM1(2),AM1(3),AM1(4),AM1(5),AM1(6)
 42  FORMAT(4X,6(6X,F4.0))
     WRITE(*,71)
 71  FORMAT(10X,'M21',7X,'M22',7X,'M23',7X,'M24',7X,'M25',7X,'M26')
     WRITE(*,72) AM2(1),AM2(2),AM2(3),AM2(4),AM2(5),AM2(6)
 72  FORMAT(4X,6(6X,F4.0))
       WRITE(*,*) 'REPEAT ; Y ?'
       READ(*,'(A1)') IN
       IF (IN.EQ.'Y') GOTO 5
        mode=2
        call QSMODE(mode)
        STOP
        END
```

```
C **************  ISDGSS *****************
C       W. N. SHARPE, JR. JUNE 15, 1989
C
C       THIS IS THE 2-CHANNEL PROGRAM USING DIODE ARRAYS.
C       IT WRITES EVERY POINT TO THE FILE AS IT IS TAKEN; NOT
C       AT THE END OF A CYCLE. LINK WITH ATLFOR.LIB
C       IT STARTS IN TENSION AND REVERSES LOADING DIRECTION WHEN
C       `MAXIMUM STRAIN' IS REACHED IN EITHER TENSION OR
C       COMPRESSION.

$STORAGE:2
$INCLUDE:'ATLDEFS.FOR'
$INCLUDE:'ATLERRS.FOR'

C------DIMENSION FOR ATLAB
        INTEGER*2 STATUS,SCANCOUNT,RLB,AX(1024),NOB1
        INTEGER*2 ADCHANNELS(16),ADGAINS(16)
        INTEGER*4 BL
        REAL*4 RATE

C------DIMENSION FOR COMPUTATION
      INTEGER IRAM(1200)
      INTEGER*2 AV1(500),AV2(500),AV(500),SLOPE1,SLOPE2
      INTEGER*2 NOS,HANOS,QUNOS
      REAL*4 RAM(1200),STRN
      REAL*4 CH1RAD,CH2RAD,CONST,CONST1,CONST2,CH1ALPHA,CH2ALPHA
      REAL*4 NETDISP,DISP,DISP1,DISP2,DDM,DDDM
      CHARACTER*10 SPCMN
      CHARACTER*20 FLNM1,FLNM2
      CHARACTER*12 DSTR,TSTR

C-----INPUT THE TEST INFORMATION
       WRITE(*,*)
       WRITE(*,*) '      *********************************************
     &*************'
       WRITE(*,*)
       WRITE(*,*) '      * THIS IS A PROGRAM FOR SINGLE CYCLE STRESS-STR
     &AIN CURVE TEST'
       WRITE(*,*)
       WRITE(*,*) '      *********************************************
     &*************'
       WRITE(*,*)
      WRITE(*,*) '      * ENTER THE SPECIMEN NUMBER... '
       READ(*,'(A10)') SPCMN
       WRITE (*,*)
      WRITE(*,*) '      * ENTER THE NAME OF DATA FILE... '
       READ(*,'(A20)') FLNM1
       WRITE (*,*)
      WRITE(*,*) '      * ENTER THE NAME OF HEADER FILE... '
       READ(*,'(A20)') FLNM2
       WRITE(*,*)
      WRITE(*,*) '      * ENTER GAGE LENGTH IN MICRONS... '
       READ(*,*) D0
      W RITE(*,*)
      WRITE(*,*) '       * ENTER CH1 (LOWER MIRROR) ANGLE IN DEGREES...'
       READ(*,*) CH1ALPHA
       WRITE(*,*)
      WRITE(*,*) '       * ENTER CH2 (UPPER MIRROR) ANGLE IN DEGREES...'
       READ(*,*) CH2ALPHA
       WRITE(*,*)
```

```
      WRITE(*,*) '       * ENTER THE FULL SCALE LOAD RANGE...'
       READ(*,*) TLR
   4   WRITE(*,*)
      WRITE(*,*) '      * HAVE YOU CHECKED MTS RANGE & SELECT INDICATOR
     *? (Y=1,N=2)'
       READ(*,*) IRS
         IF (IRS .NE. 1) GO TO 4
       WRITE(*,*)
      WRITE(*,*) '      * ENTER MAX. LOAD...   '
         READ(*,*) PMAX
          IF (PMAX .GT. TLR) GO TO 400
       WRITE(*,*)
      WRITE(*,*) '      * ENTER TOTAL NO. OF STEPS IN LOADING...'
         READ(*,*) NOS
       WRITE(*,*)
      WRITE(*,*) ' * ENTER FULL SCALE PLOTTER STRAIN IN PERCENT...'
        READ(*,*) FULSC
       WRITE(*,*)
      WRITE(*,*) '     * ENTER MAXIMUM STRAIN IN M/M * '
      READ(*,*) STRMAX
       WRITE(*,*)
      WRITE(*,*) '       * ENTER SAMPLING RATE IN kHz... '
      READ(*,*) RATE1

C-----  DEFINE LOAD PATHS
      QUNOS=NOS/4
      HANOS=NOS/2

      WRITE(*,*)
      WRITE(*,*) '       * WHAT IS YOUR "LOADING PATH" ? (1,2,3)...'
      WRITE(*,*)
      WRITE(*,*) '           1. R= -1.'
      WRITE(*,*)
      WRITE(*,*) '           2. R= 0.'
      WRITE(*,*)
      WRITE(*,*) '           3. R= 0.5.'
       READ(*,*) ILP
 8    WRITE(*,*)
      WRITE(*,*) '       * WHAT IS YOUR LOADING "TYPE" ? (1,2)...'
      WRITE(*,*)
      WRITE(*,*) '           1. TRIANGULAR. '
      WRITE(*,*)
      WRITE(*,*) '           2. SINE. '
       READ(*,*) ILT
        IF (ILT-2) 9,39,8

C-----MAKE AND STORE TRIANGULAR LOADING.
  9     IF (ILP-2) 19,10,15
 10      R=0.0
         PMIN=0.0
         GO TO 30
 15      R=0.5
         WRITE(*,*)
         WRITE(*,*) '      * ENTER MIN. LOAD...   '
          READ(*,*) PMIN
         WRITE(*,*)
     WRITE(*,*) '      * HAVE YOU SET INIT. LOAD (PMIN) (Y=1,N=2)...'
         READ(*,*) IIL
          IF (IIL .NE. 1) GO TO 15
            GO TO 30
```

```
 19   R=-1.0
      PMIN=-1.0*PMAX
      DP=4.0*PMAX/NOS
      DO 20 I=0,QUNOS
        RAM(I)=I*DP
 20   CONTINUE
      DO 25 I=QUNOS+1,2*QUNOS
        RAM(I)=PMAX-(I-QUNOS)*DP
 25   CONTINUE
       DO 28 I=2*QUNOS+1,NOS
        RAM(I)=-1.0*RAM(I-2*QUNOS)
 28   CONTINUE
      GO TO 79
 30   DP=(PMAX-PMIN)/HANOS
      DO 35 I=0,HANOS
        RAM(I)=PMIN+I*DP
 35   CONTINUE
      DO 38 I=HANOS+1,NOS
        RAM(I)=PMAX-(I-HANOS)*DP
 38   CONTINUE
      GO TO 79

C-----MAKE AND STORE SINE LOADING
 39      IF (ILP-2) 49,40,45
 40      R=0.0
         PMIN=0.0
         GO TO 59
 45      R=0.5
         WRITE(*,*)
         WRITE(*,*) '     * ENTER MIN. LOAD...   '
          READ(*,*) PMIN
         WRITE(*,*)
      WRITE(*,*) '     * HAVE YOU SET INIT. LOAD (PMIN) (Y=1,N=2)...'
         READ(*,*) IIL
          IF (IIL .NE. 1) GO TO 15
            GO TO 59
 49   R=-1.0
      PMIN=-1.0*PMAX
      DO 50 I=0,NOS
        RAM(I)=PMAX*SIN(6.283185*I/NOS)
 50   CONTINUE
      GO TO 79
 59   DO 60 I=0,NOS
        RAM(I)=0.5*(PMAX-PMIN)*(1-COS(6.283185*I/NOS))
 60   CONTINUE

C-----DIGITIZE THE RAMP
 79   DO 80 I=0,NOS
        IRAM(I)=NINT(RAM(I)*2048/TLR)+2048
 80   CONTINUE

C-----CALCULATE CONSTANTS
         CH1RAD=CH1ALPHA*3.141593/180.0
         CH2RAD=CH2ALPHA*3.141593/180.0
         CONST1=0.6328/SIN(CH1RAD)
         CONST2=0.6328/SIN(CH2RAD)
         KCH1=1
         KCH2=2
         IFLGCAL=0
```

```
C-----SET UP ATLAB
      status=ALINIT()
      status=ALSB(1)
      status=ALRSET()
             RATE=RATE1*1E3
             SCANCOUNT=2
             ADCHANNELS(1)=1
             ADCHANNELS(2)=2
             ADGAINS(1)=1
             ADGAINS(2)=1
           status=ALSETA(2,SCANCOUNT,ADCHANNELS,ADGAINS)
          status=ALSF(RATE)
          status=ALST(NINT(1024/RATE))
          status=ALFDL(ax(1),bl)
          status=ALDB(nobl,ax(1),1024)
          status=ALLB(nobl)
       status=ALDV(0,2048)

C-----  DECIDE WHAT TO DO
 85    WRITE(*,*)
      WRITE(*,*) '      * HAVE HOOKED UP MTS MACHINE ? (Y=1,N=2) '
       READ(*,*) IRH
         IF (IRH .NE. 1) GO TO 85
  90  WRITE(*,91)
  91  FORMAT(//,10X,'WHAT DO YOU WANT TO DO NOW ? (1,2,3,4) ')
      WRITE(*,92)
  92  FORMAT(/,12X,'1. CALIBRATE straingage.')
      WRITE(*,93)
  93  FORMAT(/,12X,'2. Run VIEW. ')
      WRITE(*,94)
  94  FORMAT(/,12X,'3. Run STRAIN2. ')
      WRITE(*,95)
  95  FORMAT(/,12X,'4. Abort ',/)
      READ(*,*) IV1
      IF (IV1-2) 300,100,98
  98  IF (IV1-4) 200,400,400

C **********
C    VIEW
C **********
  100      status=ALDV(0,IRAM(0))

C------ACQUISITION
          status=ALBAD()
          status=ALRELB(1,RLB)
          status=ALRETB(RLB)
          status=ALSTOP()

C------ SPLIT AX INTO AV1 & AV2
        DO 110 K=1,500
           AV1(K)=(AX(2*K+7)+AX(2*K+9)+AX(2*K+11))/3
           AV2(K)=(AX(2*K+8)+AX(2*K+10)+AX(2*K+12))/3
 110    CONTINUE

C-----FIND CENTRAL,RIGHT,AND LEFT MINIMUM CENTERS IN CH1,CH2
       CALL FRGC (AV1,MCC1,MRC1,MLC1,MSPR1,MSPL1,IFERR)
        IF (IFERR .EQ. 0) GO TO 120
       WRITE(*,116)
  116 FORMAT(//,5X,'* MINIMUM CAN NOT BE FOUND WITHIN SET UP RANGE
     + IN CH1')
```

```
  120  CALL FRGC (AV2,MCC2,MRC2,MLC2,MSPR2,MSPL2,IFERR)
        IF (IFERR .EQ. 0) GO TO 130
        WRITE(*,126)
  126 FORMAT(//,5X,'* MINIMUM CAN NOT BE FOUND WITHIN SET UP RANGE
     + IN CH2')

C-----OUTPUT MINIMUM CENTER MESSAGE
  130    WRITE(*,136)
  136  FORMAT(//,13X,'MCC',7X,'MRC',7X,'MLC',7X,'MSPR',6X,'MSPL')
         WRITE(*,146) KCH1,MCC1,MRC1,MLC1,MSPR1,MSPL1
         WRITE(*,146) KCH2,MCC2,MRC2,MLC2,MSPR2,MSPL2
  146    FORMAT(/,4X,'CH',I1,6X,I3,4(7X,I3))
        WRITE(*,*)
        WRITE(*,*) ' SPACING MUST BE > 80 AND < 150 '
         MCO1 = MCC1
         MCO2 = MCC2
        GO TO 90

C ****************
C     STRAIN2
C ****************
 200  CONTINUE
      IRECL=8
          OPEN(1,file=FLNM1,status='NEW',access='DIRECT',
     &form='UNFORMATTED',recl=IRECL)
          OPEN(2,file=FLNM2,status='NEW',access='SEQUENTIAL',
     &form='FORMATTED')
          WRITE(*,*)
         WRITE(*,*) '     * ENTER THE DATE ( mmm_dd_yyyy )...'
         READ (*,'(A12)') DSTR
          WRITE(*,*)
         WRITE(*,*) '     * ENTER THE TIME ( hh:mm )...'
         READ (*,'(A12)') TSTR

C-------WRITE HEADER
         WRITE(2,809) FLNM1
 809     FORMAT(/,'      1. TEST DATA FILE NAME : ',A20)
         WRITE(2,812) FLNM2
 812     FORMAT(/,'      2. HEADER FILE NAME : ',A20)
          WRITE(2,815) SPCMN
 815     FORMAT(/'      3. SPCMN NUMBER : ',A10)
         WRITE(2,818) DSTR,TSTR
 818     FORMAT(/,'      4. TEST DATE/TIME : ',A12,'/',A12)
         WRITE(2,824) PMAX,PMIN
 824     FORMAT(/,'      5. MAX/MIN LOAD : ',F8.0,'/',F8.0)
         WRITE(2,827) TLR
 827     FORMAT(/,'      6. FULL SCALE LOAD RANGE : ',F8.0)
         WRITE(2,830) NOS
 830     FORMAT(/,'      7. NO. OF LOADING STEPS : ',I4)
         WRITE(2,836) DO
 836     FORMAT(/,'      8. ISDG GAGE LENGTH : ',F5.0)
         WRITE(2,839) CH2ALPHA,CH1ALPHA
 839  FORMAT(/,'      9. UPPER/LOWER MIRROR REFL ANGLE :',F5.1,'/',F5.1)
         WRITE(2,842) GF
 842     FORMAT(/,'     10. STRAINGAGE GAGE FACTOR : ',F7.3)
         WRITE(2,845) RATE1
 845     FORMAT(/,'     11. SAMPLING RATE : ',F5.1,' Khz.')
         WRITE(2,848)
 848     FORMAT(/,'     13. INITIAL FRINGE PATTERN : ')
         WRITE(2,851)
```

```
 851    FORMAT(//,18X,'MCC',7X,'MRC',7X,'MLC',7X,'MSPR',6X,'MSPL')
          WRITE(2,854) KCH1,MCC1,MRC1,MLC1,MSPR1,MSPL1
          WRITE(2,854) KCH2,MCC2,MRC2,MLC2,MSPR2,MSPL2
 854    FORMAT(/,9X,'CH',I1,6X,I3,4(7X,I3))
         CLOSE(2)

C------ BEGIN TEST
          WRITE(*,*)
         WRITE(*,*) '      * ARE YOU READY TO START TEST ? (Y=1,N=2)'
          READ (*,*) IT1
            IF (IT1 .NE. 1) GO TO 400
            DDDM1=0.0
            DDDM2=0.0
          status=ALDV(1,2048)

         DO 289 L=0,NOS

C        FOLLOWING LINES EXPANDED TO PRINT MCO1,2
           WRITE(*,204) L,MCO1,MCO2
 204       FORMAT(I5,5X,I5,5X,I5)

C------ACQUISITION
           status=ALBAD()
           status=ALRELB(1,RLB)
           status=ALRETB(RLB)
           status=ALSTOP()
           status=ALAV(0,1,LD)
           IF (IFLGCAL-1) 208,206,208
  206      status=ALAV(5,1,IGV)
           GV=(IGV-2048)/204.8
           IRSG=10000.0*(GV-GV0)/(GVS-GV0)/GF
  208    CONTINUE

C-----   1OAD OUT
           status=ALDV(0,IRAM(L))

C------SPLIT AX INTO AV1 & AV2
          DO 210 K=1,498
          AV1(K)=(AX(2*K+7)+AX(2*K+9)+AX(2*K+11)+AX(2*K+13)+AX(2*K+15)
     *    +AX(2*K+17)+AX(2*K+19)+AX(2*K+21)+AX(2*K+23)+AX(2*K+25))/10
          AV2(K)=(AX(2*K+8)+AX(2*K+10)+AX(2*K+12)+AX(2*K+14)+AX(2*K+16)
     *    +AX(2*K+18)+AX(2*K+20)+AX(2*K+22)+AX(2*K+24)+AX(2*K+26))/10
 210     CONTINUE

C----    CALL DISPL2
      CALL DSPL2 (AV1,KCH1,L,CONST1,MCO1,MSPR1,MSPL1,DDDM1,DDDM2,DISP1,I
     *FERR)
           IF (IFERR .EQ. 0) GO TO 230
          WRITE (*,212)
  212 FORMAT(//,5X,'*** WARNING : MINIMUM CAN NOT BE FOUND FOUND ***')
          WRITE(*,216) L
  216 FORMAT(/,8X,'TEST STOP AT STEP # ',I4)
          WRITE(*,213)
  213  FORMAT(//,13X,'MCO',7X,'MSPR',6X,'MSPL')
           WRITE(*,214) KCH1,MCO1,MSPR1,MSPL1
  214     FORMAT(/,4X,'CH',I1,3(7X,I3),//)
      WRITE(*,222)
 222  FORMAT(//,10X,'WHAT DO YOU WANT TO DO NOW ? (1,2,3) ')
      WRITE(*,223)
 223  FORMAT(/,12X,'1. Continue... ')
```

```
      WRITE(*,224)
 224  FORMAT(/,12X,'2. Run View... ')
      WRITE(*,225)
 225  FORMAT(/,12X,'3. Abort... ',/)
      READ(*,*) ID
      IF (ID-2) 230,100,235

 230  CALL DSPL2 (AV2,KCH2,L,CONST2,MCO2,MSPR2,MSPL2,DDDM1,DDDM2,DISP2,I
     *FERR)
          IF (IFERR .EQ. 0) GO TO 240
         WRITE(*,212)
         WRITE(*,216) L
         WRITE(*,213)
         WRITE(*,214) KCH2,MCO2,MSPR2,MSPL2
         WRITE(*,222)
         WRITE(*,223)
         WRITE(*,224)
         WRITE(*,225)
      READ(*,*) ID
        IF (ID-2) 240,100,235
  235     NOP=L-1
           GO TO 400
  240    NETDISP=(DISP2-DISP1)/2.0
         STRN=NETDISP/D0
         ISDG=STRN*1000000.0
         ISTRN=NINT(STRN*204800/FULSC)+2048

C------OUTPUT TO OSCILLOSCOPE
         status=ALDV(1,ISTRN)

C------STORE ISDG,LOAD AND RSG
C
C      NOTE!!!  ISDG AND RSG ARE STORED IN MICRO-STRAIN.
C               LOAD IS STORE IN DIGITAL VALUE

            WRITE(1,REC=L+1) L,ISDG,LD,IRSG
        IF (STRN-STRMAX) 289,90,90

  289       CONTINUE

               GO TO 90

C *************************
C   STRAINGAGE CALIBRATION -- FOR ONE CHANNEL
C *************************
 300   CONTINUE
  305   WRITE(*,*)
      WRITE(*,*) '       * ENTER THE GAGE FACTOR...'
       READ(*,*) GF
 310   WRITE(*,*)
      WRITE(*,*) '       * BALANCED THE BRIDGE ? (Y=1,Y=2)'
       READ(*,*) ISC1
         IF (ISC1 .NE. 1) GO TO 310
         status=ALAV(5,1,IGV0)
          GV0=(IGV0-2048)/204.8
  312  WRITE(*,*)
      WRITE(*,*) '       * PUSHED DOWN THE CAL RESISTOR ? (Y=1,Y=2)'
       READ(*,*) ISC2
         IF (ISC2 .NE. 1) GO TO 312
          status=ALAV(5,1,IGVS)
```

```
        GVS=(IGVS-2048)/204.8
        IFLGCAL=1
        GO TO 90

C----   STOP THE PROGRAM
  400     status=ALSTOP()
        CLOSE(1)
       WRITE(*,410)
 410  FORMAT(///,5X,'***  ISDG finished ***',///)
      STOP
      END

C     ***********************************************************
      SUBROUTINE FRGC (AV,MCCN,MRCN,MLCN,MSPRN,MSPLN,IFERR)
C     ***********************************************************
      INTEGER*2 AV(500),SLOPE1,SLOPE2
      IFERR=0
C-----SET UP MINIMUM RANGE
       WRITE(*,*)
      WRITE(*,*) ' LOCATION OF LEFT MINIMUM     '
       READ(*,*) M1
       WRITE(*,*)
      WRITE(*,*) ' LOCATION OF CENTER MINIMUM     '
       READ(*,*) M2
       WRITE(*,*)
      WRITE(*,*) ' LOCATION OF RIGHT MINIMUM     '
       READ(*,*) M3
                    IRR=M3 + 20
                    IRL=M3 - 20
                    IMR=M2 + 20
                    IML=M2 - 20
                    ILR=M1 + 20
                    ILL=M1 - 20
C-----FIND CENTRAL MINIMUM
      CALL MINC2 (AV,IMR,IML,MCCN,IFERR)
         IF (IFERR .NE. 0) GO TO 40
C-----FIND RIGHT MINIMUM
      CALL MINC2 (AV,IRR,IRL,MRCN,IFERR)
         IF (IFERR .NE. 0) GO TO 40
C-----FIND LEFT MINIMUM
      CALL MINC2 (AV,ILR,ILL,MLCN,IFERR)
         IF (IFERR .NE. 0) GO TO 40
C-----CALCULATE MINIMUM SPACING
         MSPRN=MRCN-MCCN
         MSPLN=MCCN-MLCN
   40 Return
      End

C     ***********************************************************
      SUBROUTINE DSPL2 (AV,KCH,L,CONST,MCO,MSPR,MSPL,DDDM1,DDDM2,DISP,IF
     *ERR)
C     ***********************************************************
      INTEGER*2 AV(500)
      REAL*4 DDM,DDDM1,DDDM2,DISP,CONST

C-----FIND CENTRAL MINIMUM
      IF (L-0) 60,40,50
   40    M1=MCO+20
         M2=MCO-20
          GO TO 60
```

```
   50     M1=MCO+20
          M2=MC0-20
   60 CALL MINC2(AV,M1,M2,MCC,IFERR)
          IF (IFERR .NE. 0) GO TO 600
          IF (L-0) 600,70,80
   70     DM=0
           GO TO 90
   80     DM=MCC-MCO
   90     IF (MCC-250) 100,300,300

C-----FIND RIGHT MINIMUM
  100     IF (L-0) 600,110,120
  110     M1=MCC+MSPR+20
          M2=MCC+MSPR-20
           GO TO 130
  120     M1=MCC+MSPR+20
          M2=MCC+MSPR-20
  130 CALL MINC2(AV,M1,M2,MRC,IFERR)
          IF (IFERR .NE. 0) GO TO 600
           MSPR=MRC-MCC
           DDM=DM/MSPR
      IF (MCC-170) 200,140,140
  140     MCO=MCC
           GO TO 500
  200     MCO=MRC
          MSPR=MSPL
           GO TO 500

C-----FIND LEFT MINIMUM
  300     IF (L-0) 600,310,320
  310     M1=MCC-MSPL+20
          M2=MCC-MSPL-20
           GO TO 330
  320     M1=MCC-MSPL+20
          M2=MCC-MSPL-20
  330 CALL MINC2(AV,M1,M2,MLC,IFERR)
          IF (IFERR .NE. 0) GO TO 600
          MSPL=MCC-MLC
          DDM=DM/MSPL
        IF (MCC-330) 340,340,350
  340     MCO=MCC
           GO TO 500
  350     MCO=MLC
          MSPR=MSPL

C-----CALCULATE DDDM AND DISP

  500       IF (KCH-2) 510,520,600
  510       DDDM1=DDDM1+DDM
            DISP=DDDM1*CONST
            GO TO 600

  520       DDDM2=DDDM2+DDM
            DISP=DDDM2*CONST

  600      Return
           End

C     ****************************************************************
```

```
      SUBROUTINE MINC2(AV,IBGN,ITMN,MC,IFERR)
C    ***********************************************************
       INTEGER*2 AV(500),LHV,RHV,SLOPE
      IFERR=1
      DO 20 I=IBGN,ITMN,-1
         LHV=AV(I-4)+AV(I-3)+AV(I-2)+AV(I-1)
         RHV=AV(I+4)+AV(I+3)+AV(I+2)+AV(I+1)
       SLOPE=LHV-RHV
      IF (SLOPE .LE. 0.0) GO TO 20
         MC=I
         IFERR=0
         GO TO 30
   20 CONTINUE
   30 Return
      End
```

```
C *************  ISDGSSR  **********************
C       W. N. SHARPE, JR. JUNE 19, 1989
C
C       THIS IS A PROGRAM TO CONVERT FROM BINARY TO ASCII
C       AND SCREEN-PLOT DATA FROM ISDGSS. LINK WITH
C       GRAFEX33/SE:1024.

$STORAGE:2

C-----  DIMENSIONS
      REAL*4 STRN(1202),ALD(1202),RSG(1202),MSTRN(1202)
      INTEGER*2 L,ISDG(1202),LD(1202),IRSG(1202)
      CHARACTER*20 FLNM1,FLNM2

C-----  INPUT INFORMATION
      WRITE(*,*)
      WRITE(*,*) '   ENTER OLD DATA FILE NAME...'
      READ(*,'(A20)') FLNM1
      WRITE(*,*)
      WRITE(*,*) '   ENTER TOTAL NO. OF POINTS TO READ...'
      READ(*,*) NOP
      WRITE(*,*)
      WRITE(*,*) '   ENTER NEW DATA FILE NAME...'
      READ(*,'(A20)') FLNM2

      IRECL=8

C-----  READ AND CONVERT DATA
             open(1,file=FLNM1,status='OLD',access='direct',
     &        FORM='UNFORMATTED',RECL=IRECL)

       DO 30 L=1,NOP+1
        READ(1) K,ISDG(L),LD(L),IRSG(L)
  30   CONTINUE
       CLOSE(1)

       DO 40 I=1,NOP+1
          STRN(I)=ISDG(I)/1000000.0
          RSG(I)=IRSG(I)/1000000.0
          ALD(I)=1000.0*(LD(I)-2048.0)/204.8
          MSTRN(I)=ISDG(I)*1.0
  40   CONTINUE

      OPEN(2,FILE =FLNM2,STATUS='NEW',
     &        ACCESS='SEQUENTIAL', FORM ='FORMATTED')

      DO 100 L=1,NOP+1
         WRITE(2,99) STRN(L),ALD(L),RSG(L)
 99      FORMAT(5X,E13.4,2X,F9.2,2X,E13.4)
 100  CONTINUE
      CLOSE(2)

       WRITE(*,*) 'DO YOU WANT TO PLOT, Y=1 ? '
       READ(*,*) IP
       IF(IP.NE.1) GOTO 200

C-----  INPUT PLOT DATA
105    iorg=1
       xscale=1
       WRITE(*,*) 'X start?'
```

```
      READ(*,*) xst
      WRITE(*,*)
      WRITE(*,*) 'X finish?'
      READ(*,*) xfin
      WRITE(*,*)
      WRITE(*,*) 'Y start?'
      READ(*,*) yst
      WRITE(*,*)
      WRITE(*,*) 'Y finish?'
      READ(*,*) yfin
      WRITE(*,*)
      itype=1
      npt=NOP

C     SWITCH TO GRAPHICS MODE
      mode=16
      CALL QSMODE(mode)
      CALL QSETUP(0,4,4,3)
      call QPTABL(iorg,xscale,xst,xfin,yst,yfin,itype,npt,MSTRN,ALD)

C     POSITION CURSOR TO EXIT
      CALL QCMOV(0,3)
      WRITE(*,*)'REPEAT PLOT? -- Y = 1'
      READ(*,*) IRP
      IF(IRP.NE.1) GOTO 96
      GOTO 105
96    CONTINUE
      WRITE(*,98)
      READ(*,97)
98    FORMAT(' ENTER '/' TO EXIT')
97    FORMAT(A1)

C     SWITCH BACK TO TEXT MODE
      mode=2
      CALL QSMODE(mod
  200  STOP
        END
```

```
C ******************** ISDG **************************
C       W. N. SHARPE, JR.  JUNE 15, 1989
C
C       THIS IS THE 2-CHANNEL PROGRAM USING DIODE ARRAYS.
C       TEST RUNS UNDER LOAD CONTROL.
C       IT WRITES ALL THE DATA POINTS OF A CYCLE TO THE
C       FILE AT THE END OF THE CYCLE. LINK WITH ATLFOR.LIB.
```

**The following are the only two parts of ISDG that are different from ISDGSS.**

**************************************************************************

```
C ****************
C     STRAIN2
C ****************
 200  CONTINUE
       IRECL=(NOS*3+4)*2
          OPEN(1,file=FLNM1,status='NEW',access='DIRECT',
     &form='UNFORMATTED',recl=IRECL)
```

**************************************************************************

```
C------ BEGIN TEST
         WRITE(*,*)
        WRITE(*,*) '     * ARE YOU READY TO START TEST ? (Y=1,N=2)'
         READ (*,*) IT1
           IF (IT1 .NE. 1) GO TO 400
            DDDM1=0.0
           DDDM2=0.0

      DO 299 N=1,NCY

C----- WRITE CYCLE NO.
            WRITE(*,204) N
  204      FORMAT(1X,I4)

C-----  DO A CYCLE
        DO 289 L=0,NOS

C------ACQUISITION
          status=ALBAD()
          status=ALRELB(1,RLB)
          status=ALRETB(RLB)
          status=ALSTOP()
          status=ALAV(0,1,LD(L))
          IF (IFLGCAL-1) 208,206,208
  206     status=ALAV(5,1,IGV)
          GV=(IGV-2048)/204.8
          IRSG(L)=10000.0*(GV-GV0)/(GVS-GV0)/GF
  208   CONTINUE

C-----  LOAD OUT
          status=ALDV(0,IRAM(L))

C------SPLIT AX INTO AV1 & AV2
          DO 210 K=1,498
```

```
      AV1(K)=(AX(2*K+7)+AX(2*K+9)+AX(2*K+11)+AX(2*K+13)+AX(2*K+15)
     # +AX(2*K+17)+AX(2*K+19)+AX(2*K+21)+AX(2*K+23)+AX(2*K+25))/10
      AV2(K)=(AX(2*K+8)+AX(2*K+10)+AX(2*K+12)+AX(2*K+14)+AX(2*K+16)
     # +AX(2*K+18)+AX(2*K+20)+AX(2*K+22)+AX(2*K+24)+AX(2*K+26))/10
 210    CONTINUE

C----   CALL DSPL2
      CALL DSPL2 (AV1,KCH1,L,CONST1,MCO1,MSPR1,MSPL1,DDDM1,DDDM2,DISP1,I
     *FERR)
          IF (IFERR .EQ. 0) GO TO 230
         WRITE (*,212)
 212  FORMAT(//,5X,'*** WARNING : MINIMUN CAN NOT BE FOUND FOUND ***')
         WRITE(*,216) N,L
 216  FORMAT(/,8X,'TEST STOP AT CYCLE #',I4,'         STEP # ',I4)
         WRITE(*,213)
 213   FORMAT(//,13X,'MCO',7X,'MSPR',6X,'MSPL')
          WRITE(*,214) KCH1,MCO1,MSPR1,MSPL1
 214     FORMAT(/,4X,'CH',I1,3(7X,I3),//)
      WRITE(*,222)
 222  FORMAT(//,10X,'WHAT DO YOU WANT TO DO NOW ? (1,2,3) ')
      WRITE(*,223)
 223  FORMAT(/,12X,'1. Continue... ')
      WRITE(*,224)
 224  FORMAT(/,12X,'2. Run View... ')
      WRITE(*,225)
 225  FORMAT(/,12X,'3. Abort... ',/)
      READ(*,*) ID
      IF (ID-2) 230,100,400
 230  CALL DSPL2 (AV2,KCH2,L,CONST2,MCO2,MSPR2,MSPL2,DDDM1,DDDM2,DISP2,I
     *FERR)
          IF (IFERR .EQ. 0) GO TO 240
         WRITE(*,212)
         WRITE(*,216) N,L
         WRITE(*,213)
         WRITE(*,214) KCH2,MCO2,MSPR2,MSPL2
         WRITE(*,222)
         WRITE(*,223)
         WRITE(*,224)
         WRITE(*,225)
      READ(*,*) ID
       IF (ID-2) 240,100,400
 240     NETDISP=(DISP2-DISP1)/2.0
         STRN=NETDISP/D0
         ISDG(L)=STRN*1000000.0
         ISTRN=NINT(STRN*204800/FULSC)+2048

C------OUTPUT TO OSCILLOSCOPE
         status=ALDV(1,ISTRN)

C------STORE ISDG,LOAD AND RSG
C
C       NOTE!!!  ISDG AND RSG ARE STORED IN MICRO-STRAIN.
C                LOAD IS STORE IN DIGITAL VALUE

 289        CONTINUE
            WRITE(1,REC=N) N,(ISDG(L),LD(L),IRSG(L),L=0,NOS)
 299         CONTINUE
               GO TO 90
```

```
C **************** ISDGR  *************
C       W. N. SHARPE, JR. JUNE 19, 1989
C
C       THIS IS A PROGRAM TO CONVERT FROM BINARY TO
C       ASCII AND SCREEN-PLOT DATA FROM ISDG. LINK
C       WITH GRAFEX33/SE:1024.

C-----  DIMENSION
      REAL*4 STRN(1200),ALD(1200),RSG(1200),MSTRN(1200)
      INTEGER*2 N,ISDG(1200),LD(1200),IRSG(1200)
      CHARACTER*20 FLNM1,FLNM2

C-----  INPUT TEST INFORMATION
      WRITE(*,*)
      WRITE(*,*) '    ENTER OLD DATA FILE NAME...'
      READ(*,'(A20)') FLNM1
      WRITE(*,*)
      WRITE(*,*) '    ENTER TOTAL NO. OF STEPS PER CYCLE IN TEST...'
      READ(*,*) NOS
 30   WRITE(*,*)
      WRITE(*,*) '    ENTER THE Nth CYCLE No. ...'
      READ(*,*) N
      WRITE(*,*)
      WRITE(*,*) '    ENTER NEW DATA FILE NAME...'
      READ(*,'(A20)') FLNM2
      IRECL=(NOS*3+4)*2

C-----  READ AND CONVERT DATA
             open(1,file=FLNM1,status='OLD',access='direct',
     &        FORM='UNFORMATTED',RECL=IRECL)
       READ(1,REC=N) N,(ISDG(L),LD(L),IRSG(L),L=0,NOS)
       CLOSE(1)

       DO 40 I=0,NOS
          STRN(I)=ISDG(I)/1000000.0
          RSG(I)=IRSG(I)/1000000.0
          ALD(I)=1000.0*(LD(I)-2048.0)/204.8
          MSTRN(I)=ISDG(I)*1.0
  40    CONTINUE

      OPEN(2,FILE =FLNM2,STATUS='NEW',
     &        ACCESS='SEQUENTIAL', FORM ='FORMATTED')
      WRITE(2,89) N
 89   FORMAT(/,2X,I5)

      DO 100 L=0,NOS
         WRITE(2,99) STRN(L),ALD(L),RSG(L)
 99      FORMAT(5X,E13.4,2X,F9.2,2X,E13.4)
100   CONTINUE
       CLOSE(2)
       WRITE(*,*) 'DO YOU WANT TO PLOT, Y=1 ? '
       READ(*,*) IP
       IF(IP.NE.1) GOTO 200

C-----  INPUT PLOT INFORMATION
105     iorg=1
        xscale=1
        WRITE(*,*) 'X start?'
        READ(*,*) xst
        WRITE(*,*)
```

2

```
        WRITE(*,*) 'X finish?'
        READ(*,*) xfin
        WRITE(*,*)
        WRITE(*,*) 'Y start?'
        READ(*,*) yst
        WRITE(*,*)
        WRITE(*,*) 'Y finish?'
        READ(*,*) yfin
        WRITE(*,*)
        itype=1
        npt=NOS

C       SWITCH TO GRAPHICS MODE
        mode=16
        CALL QSMODE(mode)
        CALL QSETUP(0,4,4,3)
        call QPTABL(iorg,xscale,xst,xfin,yst,yfin,itype,npt,MSTRN,ALD)

C       POSITION CURSOR TO EXIT
        CALL QCMOV(0,3)
        WRITE(*,*)'REPEAT PLOT? -- Y = 1'
        READ(*,*) IRP
        IF(IRP.NE.1) GOTO 96
        GOTO 105
96      CONTINUE
        WRITE(*,98)
        READ(*,97)
98      FORMAT(' ENTER '/' TO EXIT')
97      FORMAT(A1)

C       SWITCH BACK TO TEXT MODE
        mode=2
        CALL QSMODE(mode)
  200    STOP
          END
```

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16. Abstract

A system for measuring the relative in-plane displacement over a gage length as short as 100 micrometers is described. Two closely spaced indentations are placed in a reflective specimen surface with a Vickers microhardness tester. Interference fringes are generated when they are illuminated with a He-Ne laser. As the distance between the indentations expands or contracts with applied load, the fringes move. This motion is monitored with a minicomputer-controlled system using linear diode arrays as sensors.

Characteristics of the system are: gage length ranging from 50 to 500 micrometers, but 100 micrometers is typical; least-count resolution of approximately 0.0025 micrometer; and sampling rate of 13 points per second. In addition, the measurement technique is non-contacting and non-reinforcing. It is useful for strain measurements over small gage lengths and for crack opening displacement measurements near crack tips.

This report is a detailed description of a new system recently installed in the Mechanics of Materials Branch at the NASA Langley Research Center. The intent is to enable a prospective user to evaluate the applicability of the system to a particular problem and assemble one if needed.

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