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ELECTRO OPTICAL SYSTEM TO MEASURE STRAINS AT HIGH TEMPERATURE

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SIX MONTH REPORT

INTRODUCTION

This phase of the research program started the 7/17/90.

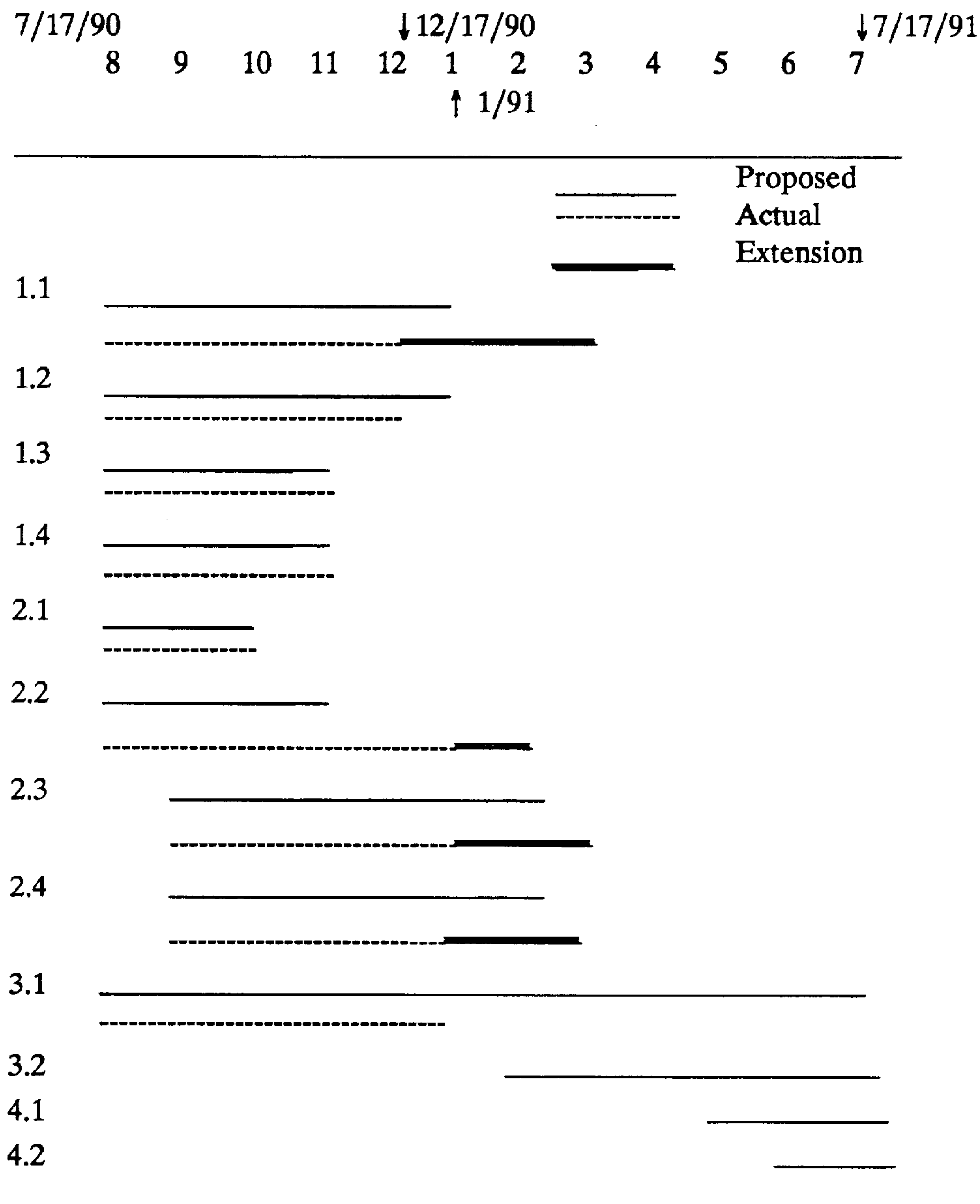
The goal of the proposal is to develop a prototype of the electro-optics system for the measurement of strains in structures at high temperatures and to perform a test under field conditions. To achieve this goal the required work was organized in the following tasks: 1) Research task, 2) design and construction task, 3) testing task, and 4) final evaluation task. The bar graphs I and II gives the work schedule according to the proposal (full lines), the dashed lines represent the actual progress. As it can be seen the program has progressed according to the planned schedule.

1. RESEARCH TASK

1.1. Correction of the Effect of Vibrations and Thermal Currents by Means of an Active Compensation System.

The compensation system has been designed and assembled, details of the system are given in Appendix I. The system is based on the use of fiber optics, and is an integral part of the illumination system of the prototype as it will be shown later. The system has been tested and fringe compensation has been experimentally verified, that is the system works and it is able to lock the fringes to the output of a photodiode sensor. Currently the system is under test to establish characteristic properties, responses, and optimization of the system parameters. A numerical model of the system has been developed an is used in conjunction with the experimental measurements to optimize the system performance.

WORK SCHEDULE



1.1 Correction effect of vibrations - thermal currents

1.2 Reduction speckle noise

1.3 Compensation rigid body motions

1.4 Removal of phase errors by dynamic reading

2.1 Preliminary design
2.2 Final design
2.3 Assembling system
2.4 Drivers and software
3.1 Tests high temp. oven
3.2 Tests - Testing Bay
4.1 Evaluation
4.2 Recommendations

1.2. Reduction of the Speckle Noise by Means of Electronic Filter and TV Signal Reconstruction Circuit.

This concept was explored and a basic circuit has been designed and partially assembled. The main purpose of this component is reducing the speckle in the real time visual display of the results in the monitor. Since this circuit does not play a role in the quantitative aspects of the data reduction, our attention has focused in the more important components and for the time being no further work has been done in this aspect of the problem.

1.3. Compensation of the Rigid Body Motions by Mounting the Camera in a Universal Motion System.

This concept was pursued and implemented with success. Fringe quality can be improved by applying corrections to the rigid body motions of the object under analysis.

1.4. Removal of Phase Errors Left by the Active Compensation System by Dynamic Reading

A great deal of work has been done in this particular aspect of the problem. We will summarize the main results of this research. Main causes of phase errors are: a) vibrations, b) thermal tubulence. We will discuss each one of these two effects. The vibrations will be compensated by the active compensation system. A computer program has been developed to perform dynamic readings, thus eliminating any small residual effects due to vibrations. The program has been tested and has shown a noticeable improvement in fringe contrast when it is applied. It has been found also that the quality of the images can be improved by shuttering the camera. It has been found that one can use very short exposures and obtain good quality images. We plan to purchase in the future a camera with a shutter. The explanation of the quality improvement of the images with respect to the images that can be obtained with the regular framing time of 1/30 of second, is statistical. Since the vibrating body expends most of the time in the extreme positions, when the exposure is short this is most likely position to be recorded. Consequently the addition of the passive compensation that is built in our present set up with the reduction of the exposure can handle normal vibration conditions. This means that one can record images without resorting to active compensation. In spite of this observation, we have concluded that the introduction of an active compensation is still a very useful feature to have since it will make it possible real time viewing of the fringes. We think that real time viewing is a feature that is very useful under many circumstances.

The effect of the thermal turbulence is not so straightforward to remove as the vibration effect. This effect is due to the gradients of density produced by the air convection currents. We have observed that in our oven, since we modified the front part of it to introduce two additional windows for vertical viewing and reducing the angle of illumination from 45o to 30 o, the effect of the turbulence has increased. At low temperatures we get one and a half to two additional fringes that change at random at low frequencies. Recent observations at 960 Co.show both an increase in the number of fringes and in the velocity of motion. At this point is not clear why the changes in the oven have caused such a change in the thermal motion. Shuttering at high speed will freeze these fringes but will not eliminate them. The fringe compensation system will have the effect of freezing the areas that are in phase with the selected reference point and the remaining areas will be changing phase.

There is a solution for the recording of the phases due to the turbulence, the use of the Shack-Hartman sensor. The detector has a small lenses array and sensors at the focal distance of the lenses. Each lens is small enough that does not resolve the image of the object being analyzed but records the tilts of the wave front caused by the thermal oscillations. The device provides the slopes of the wave front and by integration of these slopes it is possible is possible to reconstruct the wave front. A set-up can be designed that records the image of the object in a CCD and at the same time records the phase turbulence in the sensor. The procedure to record the images free from the atmospheric turbulence is as follows, an initial image will be taken for both the object and the wave front. Both will be recorded at a shutter speed such that the motion will be frozen. Another exposure will be taken after the object under observation is loaded. The phases of the initial and the final recordings will be corrected from the thermal distortion and then subtracted to give the change of phase caused by the loading.

We are presently working with an alternative idea that is based on our observations of the thermal fluctuations. The thermal fluctuations are random and their phase is changing continuously both in space an time. The changes of phase due to the loading are constant in space and in time. If the phases of a number of patterns that contain the effect of the loading and the thermal oscillations are averaged, the phase average will converge to the phase change due to the loading, since phase of the random thermal fringes will average to zero. This solution seems to be the simplest of all possible alternatives. It requires only to have a shuttered camera to take successive snaps. This second alternative is less expensive from the point of view of the equipment that is required but will be more time consuming in the recording and processing of data.

2. DESIGN AND CONSTRUCTION TASK

2.1. Preliminary Design.

Figure 1 shows the basic conceptual design of the camera system.

The system has a number of optical an electronic components that are shown in Fig. 1. Conceptually, we can divide the system in the following sub-units: 1)

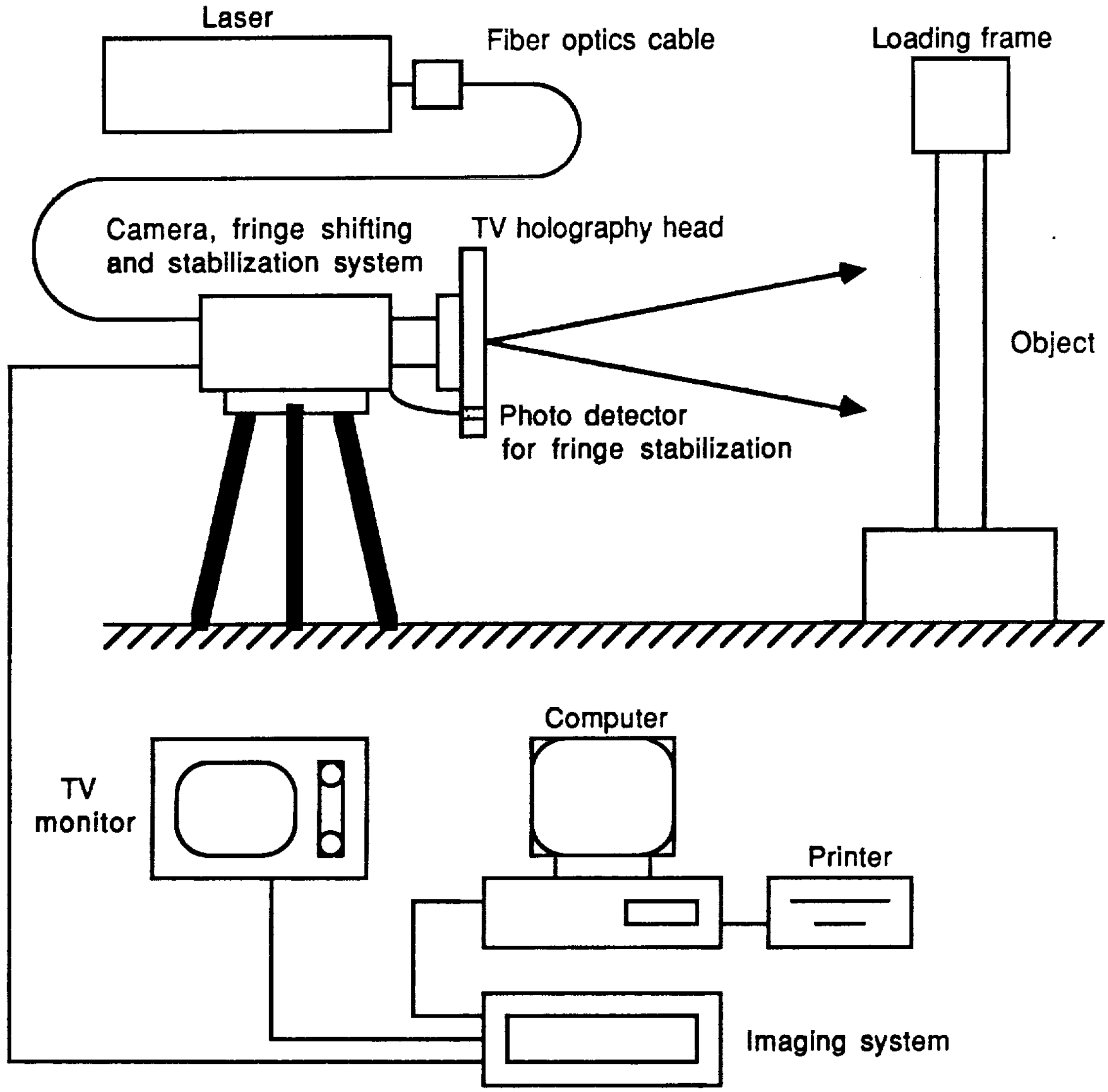


Figure 1. TV HOLOGRAPHIC SYSTEM FOR THE STRAIN ANALYSIS OF STRUCTURES SHOWING THE MAIN COMPONENTS

Illumination and light conditioning system, 2) Signal detection, 3) data gathering and manipulation, 4) Data processing, 5) Data output, and 6) Control unit. The illumination system is based on the use of single-mode fiber optics. A fiber-optics cable will connect the laser with the recording head. This choice permits:

1. A very compact design
2. There are no complex optical adjustments and not open beams since all the illumination circuit is sealed
3. Four point sources will provide the horizontal and vertical illuminations
4. A number of different lasers can be used
5. The laser will be located at a distance of several meters from the head

The illumination system and light conditioning has two sub-units: 1) fringe stabilization system and 2) fringe shifting. The fringe stabilization unit has the function of locking the phase of the observed fringes to the phase of a selected point on the analyzed body. The fringe shifting capability is built-in in the circuit that compensates the phase. A detailed description of the fringe stabilizing system is given in Appendix I. The signal detection is performed by a CCD camera with shuttering capability. The data gathering and manipulation is performed by an imaging system with the following main components: 1) analog-to-digital and digital-to- analog converter, 2) arithmetic logic unit,3) frame buffers, and 4) array processor.

The speckle interferograms give a grainy and noisy image. The speckles although contribute to the noise of the image are the information carriers and therefore in the process of information gathering must be enhanced to insure adequate signal to noise ratio. However in the final stage of data processing they must be removed. The data collected by the CCD camera are manipulated within the imaging system for optimum signal conditioning before signal processing. The data processing is performed within the imaging system using some of the logical operations that are available in the system and the specialized array processor which is capable of floating point operations. The data output is in the form of images that go to the TV monitor or data that go to the printer. The operations are controlled by a 386 PC computer.

The PC computer will also interact with the CCD camera for frame data acquisition and with the fringe compensation system for fringe shifting operations. Summarizing, an interferometer capable of operating under general field conditions has been designed that at the same time provides automatic quantification of the data.

2.2. Final Design

Work has been started in the final design of different aspects of the electronic, optics and mechanical parts. The field prototype will be assembled with the means at our disposal. This means that although there may be better solutions for the design some of the components, solutions will be restricted to the resources available at this time.

2.3. Final Assembling

The tasks of assembling of components are progressing with the development phase of the program.

2.4. Software Development

A very important step forward in the data conditioning and processing has been achieved with the acquisition of the specialized array processor. To this point our software was limited to line by line analysis due to the lack of computer speed. We have started a complete new generation of software based on two dimensional operations. The description of the main programs that have been developed is given in Appendix II.

A description of the functions of the developed software is provided in the following paragraph.

2.4.1. Signal Conditioning. The intensity of the resulting image is controlled by the automatic gain and level optimization package. After this operation, a normalization operation is introduced. The normalization software determines local intensity average values and normalizes them to the maximum range of intensities available in the system 256 gray levels.

Before the data are processed a filtering operation is needed for removal of the speckles. A 2D real Fast Fourier Transform (FFT) has been developed. This software is used to determine the band width of the signal. This program can compute the FFT of the image in few seconds.

Based on the information obtained from the previous program, the image is filtered and the speckle noise is removed.

2.4.2. Data Processing. A number of programs have been developed for data extraction. In the case of thermal patterns which are unstable due to thermal oscillations a 2-D extraction program using signals in quadrature is used. This program requires only one recording. One limitation of the program is the inability to automatically assign fringe orders. The problem is solved by introducing carrier fringes, in this case relative signs are automatically obtained and calibrating the system it is possible to obtain absolute signs.

There are other programs that have been developed, these programs require phase shifting. Descriptions are given in Appendix II.

2.4.3. Recorrelation of Two Holograms in the Presence of Rigid Body Motions. A serious limitation of holography in either the traditional form or the TV form is the amount of displacements that can be handled before fringe contrast is lost. For high module of elasticity materials and in the range of deformations of technical interest this limitation does not affect observations due to local deformations. The factor limiting the observation is rigid body motions. The loss of correlation is related to the speckle size projected to the surface under observation. The speckle size in the image plane is a function of the optical system aperture and the size on the object surface depends on the system magnification. The correlation is completely lost when the displacement is equal to the speckle size and the fringe contrast drops very rapidly beyond deformations of the order of 50 % of the speckle size. The ordinary way that one operates in holographic interferometry is to use superposition of recordings to insure the automatic correlation. However recorrelation can be applied a posteriori, an example of this is the sandwich holography. In the case of TV holography we have introduced a novel idea. The initial and the final images of the object are added together, and a 2-D FFT is performed to obtain the power spectrum of the added images. The rigid body motions produce interference fringes in the power spectrum whose frequency is related to the amount of rigid body motion and whose inclination is related to the direction of the rigid body motion. By performing the measurements at two points of the image one can determine the vector translation and the rotation magnitude that is necessary to apply to restore correlation. The program has been developed to correct for translations, the rotation correction is under development.

2.4.4. Phase Extraction Using a Computer Generated Image. One of the problems that arise when creep strains are recorded is that different stages of deformation must be compared. For this purpose is necessary to resort to sequential recording. This operation can be greatly simplified if a common reference is introduced. The phase map with respect to the reference pattern can be stored. Later different stages of deformation can be compared by subtracting phases with respect to the common reference. The reference pattern is computer generated and therefore one can have a commom reference for all the different recorded patterns. This program has been developed and succesfully tested by using the initial and final speckle patterns corresponding to a given load.

2.4.5. A Number of Programs are Still Under Development. These programs have the objective of further improving signal conditioning and processing.

3. TESTING

3.1. Testing in the High Temperature Oven

The oven was modified to allow illumination in both the horizontal and vertical direction. The modification of the oven caused a change in the thermal flow resulting in a considerable increase in the thermal disturbance. An internal glass baffle was introduced to reduce this effect. However, it was not possible to go back to the quieter operation of the previous design.

Since we have verified that the strain gages give good results at low temperature, before burning them to do the high temperature tests, we used them to verify a number of programs of data conditioning and data processing. We are now in the process of performing the high temperature tests.

The detailed description of the test is given in Appendix III. The statistical analysis of the results of the strain gages and optical measurements show that they are statistically identical, with a correlation coefficient of .998.

APPENDIX I

FRIGE MOTION COMPENSATION

Fiber Optic Holographic System with Active Fringe Stabilization

ABSTRACT:

The objective of the fringe stabilization system is to record holograms in an unstable environmental conditions. The illumination to system is derived through a pair of optical fibers formed by cleaved ends. An active phase compensation is provided in one of the fiber arm through electronics in conjunction with a piezoelectric phase modulator to nullify the phase perturbations due to unstable conditions.

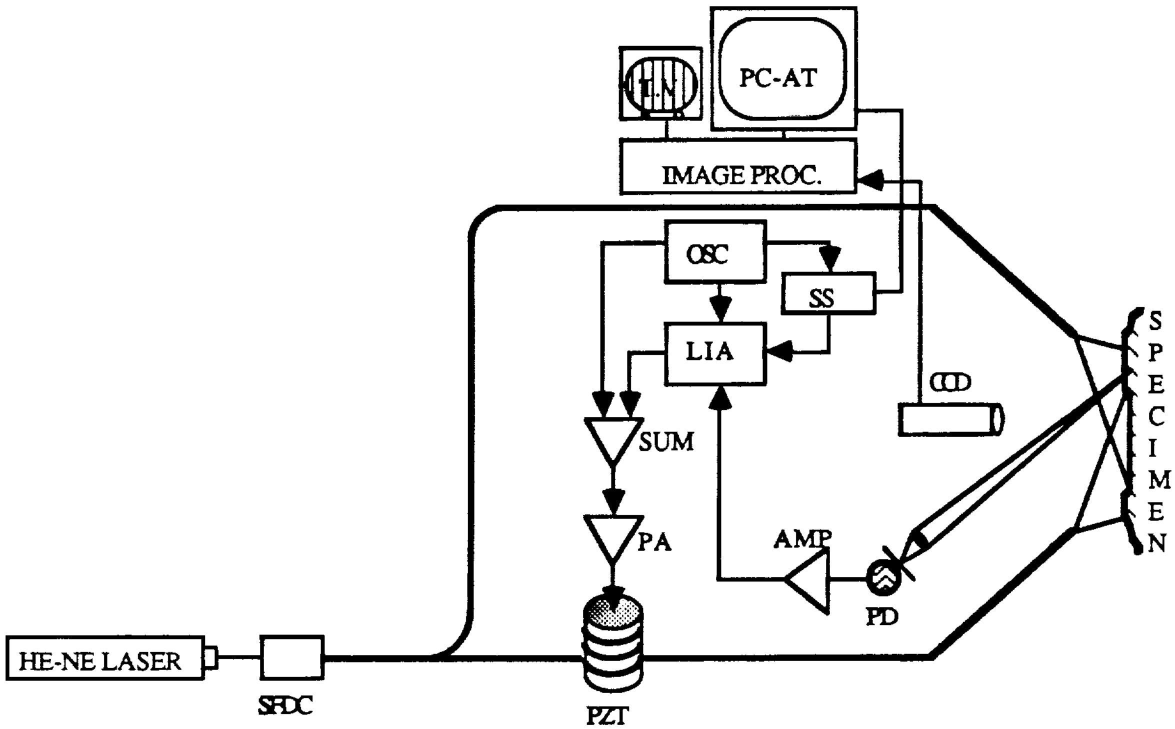
INTRODUCTION:

The non-destructive test using holographic techniques is finding ever increasing applications in industry due to the fact that it is highly sensitive to the order of less than one wave length of the laser light being used. The development of optical fiber and its successive application in interferometry has conquered the problems of conventional optics. With relative insensitivity to misalignment, highly accurate optical interferometry can be performed. Although it is insensitive to misalignments but still it suffers a major predicament when used under hostile conditions. Insignificant changes in the environmental conditions could affect the fringe stability and the information it carries extensively. This has limited the use of holographic techniques mainly to the laboratory experiments.

In order use the technique in an unstable environmental conditions with the convenience of optical fiber based holographic system, an active fringe stabilization system must be used.

SYSTEM DESCRIPTION:

The system has a number of optical and electronic components that are schematically shown in Fig 1.



SFDC - Single mode fiber directional coupler
PD - Photo-diode (Sensor)
LIA - Lock-in-amplifier

OSC - Oscillator
PA - Power amplifier

PZT - Phase modulator
AMP - Amplifier
SS - Phase step selector (0, 90, 180, 270)
SUM - Summing amplifier
CCD - Camera

Fig 1. Fringe stabilization system

Figure 1 shows the stabilization system together with the image processing sytem which work independent of each other.

Conceptually the system can be divided into three basic units: 1) illumination system, 2) piezoelectric PZT phase modulator and 3) feed back electronic control system.

The illumination system constitutes laser, directional coupler, bi-directional coupler and optical fibers. The light from the laser source is launched into the optical fiber using a fiber directional coupler. Two arms of the illumination system are splitted using a bi-directional coupler. In the experiment fiber of core diameter of 4 micrmeter and clad of 125 micrometer dia is used. There is only one time accurate alignment of fiber is required to couple maximum power of light into the fiber.

The piezoelectric phase modulator is made from Vernitron's PZT cylinder with applied field in radial direction. The fiber is wounded tightly around the PZT in calculated number of laps. The number of laps are determined by the required range of the phase compensation which is a function of applied field to the PZT.

The feed back electronic control system constitutes a sensor which produces voltage proportional to the input light. A series of electronic components processes further the signal and produces voltage proportional to the error signal which is fed to the PZT as an active feed back compensation.

EXPERIMENTAL INVESTIGATIONS:

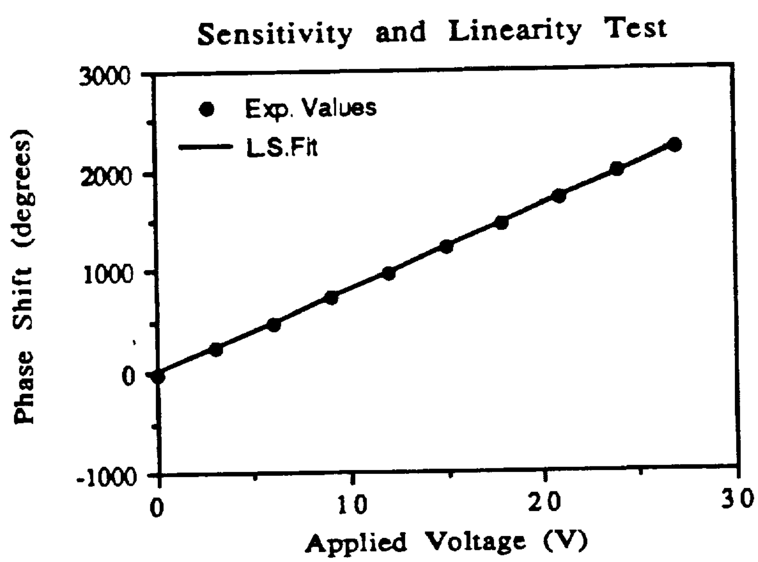
In order to solve the problem systematically, a series of individual experiments have been performed on each basic unit. Primary investigations includes tests on proper coupling of the light into the fiber and tests on PZT phase modulator including the linearity, hysteresis and dynamic response of the phase shifter.

Experimental set-up for michelson interferometer is arranged using a 5 milliwatt HE-NE laser source with laser beam dia of 0.83 mm at e^2 point. Single mode fiber of 4/125 micrometer core and clad dia is used in constructing two arms of the interferometer. Laser is launched into the fiber using Newports F916 directional coupler. About 60% of the light was successfully coupled into the fiber efficiently. Coupling light power efficiently is a function of fiber cleaving and accurate alignment. The light at the ends of two arm are made to interfere to form fringes. At this stage in order to test individually the performance of each component of the stabilization system, it is necessary to have a quite and stable environment. Therefore the entire set up is properly isolated from the environmental perturbations within reasonable means.

The piezoelectric phase shifter is constructed from Vernitron's model 5H (high sentivity soft material) PZT cylinder of 2" OD and 2" length. Twenty laps of fiber is tightly wounded around the cylinder and properly secured establishing theoretical compensation range of 5.36L where 'L' being the wave length of the laser which is

633 nm. with an applied field of 15 V. The theoretical sensitivity of the device is found to be 0.357L/V. The phase shifter is provided in one of the arm of the michelson interferometer.

The michelson interferometer set up is used to conduct tests on the PZT phase modulator to determine the quantitative experimental values for sensitivity, linearity, hysteresis and dynamic response of the device. The results are depicted in the graph below.



At this stage the tests for the sensitivity and linearity have been successfully completed and the results are very encouraging. The experimental value for sensitivity is found to be 0.225L/V and the plot of phase shift Vs applied voltage has demonstrated very good linearity of the device.

APPENDIX II

SOFTWARE DEVELOPMENT

<u>Software Development</u>

A brief description of the new softwares developed for the improved detection of displacement information in TV holography is given below.

1. <u>2-D Real FFT</u>:

This program computes the two-dimensional fast Fourier transform of an image of size up to 512 x 512 pixels and displays the 2-D power spectrum and 2-D phase spectrum of the image. A special array processor (Image processing accelerator) is used to compute the 2-D FFT of real data. This software can be used to obtain the frequency band of the displacement fringes and separate it from the unwanted noise.

2. <u>2-D Complex FFT</u>:

This program computes the 2-D FFT of complex data using the host computer. This program is slightly slower than the 2-D real FFT program, but has the advantage of handling complex data. This software can be used to perform filtering in frequency plane and obtain the displacement information using 'signals-in-quadrature' technique.

3. <u>2-D Filter</u>:

This software performs a two-dimensional filter of an image in the Fourier plane using the IPA array processor. Virtually any number and size of smooth elliptical pass (or stop) windows can be selected in the Fourier plane. The program can handle images of size up to 512 x 512 pixels. 2-D FFT program is used to obtain the frequency band where the displacement information lies. Based on the information, a Fourier filter mask is generated which is made of smooth elliptical windows. 2-D Fourier transform of the speckly fringe pattern is multiplied by the filter mask to separate the frequency spectrum of the displacement fringe pattern from that of the speckle noise. A 2-D inverse FFT of the filtered spectrum is performed to obtain the image of displacement fringes free of the speckle noise.

4. 2-D Phase Extraction using Quasi-heterodyne Technique:

This software uses a combination of optical phase modulation and digital signal processing operations to extract the phase of speckles all over the image simultaneously. Optical phase modulation is applied to the image of the object before the application of load and the speckle phases at all pixels in the image are computed. Some operations are performed on the image of the object after the application of load to obtain the phase values of deformed speckles. The phase change due to deformation is obtained by computing the difference between the phases of undeformed speckles and those of deformed speckles.

5. 2-D Phase Extraction using Signals-in-Quadrature Technique:

This program uses the 2-D FFT with digital Hilbert transform to compute the 2-D phase contour map of the displacement fringes. 2-D Fourier plane filtering can be performed before the phase extraction process, is necessary. The program first performs the 2-D FFT of the speckly fringe pattern using the IPA hardware. It then separates the fringe spectrum from the spectrum of the noise using the frequency plane filter mask. In-phase signal is obtained by the 2-D inverse FFT of the filtered spectrum. Digital Hilbert transform frequency spectrum is computed from the filtered frequency spectrum of the fringe pattern using the IPA processor. In-quadrature signal is obtained by performing the 2-D inverse FFT of Hilbert transform spectrum. The two-dimensional phase contour map of the displacement fringes is obtained using the in-phase and in-quadrature signals. This software is useful in the analysis of fringes obtained in unstable environments where it is difficult to introduce optical phase modulation.

6. Recorrelation of Two Holograms in the Presence of Rigid Body Motions:

This software detects the amount of rigid body motion in the object under test using auto-correlation technique. The initial and final images of the object are added together, and a 2-D FFT is performed to obtain the power spectrum of the added images. Rigid body motions in the object introduce Young's fringes in the power spectrum whose frequency is related to the amount of rigid body motion and whose inclination is related to the direction of rigid body motion. A 2-D FFT of the power spectrum is performed to obtain the auto-correlation function. The position of the peak in the auto-correlation function gives the amount of rigid body motion. Correlation between the two holograms is then established by shifting them relative to each other by the amount indicated by the peak position of the auto-correlation function.

7. Automatic Gain and Level Optimization:

On an interactive basis, this software automatically searches for the best gain and level combination for the analog to digital converter in order to obtain the best speckle contrast. Displacement information is carried by the speckle pattern. Therefore, high contrast displacement fringes can be obtained by optimizing the contrast of the speckle carrier.

8. Line Fourier Analysis Package:

This package can perform several signal processing operations in the space and frequency domain on a line by line basis in a very flexible and interactive way. Filtering, phase extraction, combination of signals, frequency shifting, etc. can be done for any number of data points between 3 and 512. This software is useful if one likes to perform a fast analysis of the fringes along certain lines in the image.

9. Numerical Simulation of a Feedback Fringe Stabilization System:

This software can make a numerical simulation of the dynamic behavior of a feedback fringe stabilization system. It has been used to evaluate the dynamic performance of the stabilization system being built and to optimize some of the component parameters.

10. Phase Extraction using a Computer Generated Reference Pattern:

The initial speckle pattern can be superimposed on a computer generated reference grating to form a complex moire pattern. The phase map of the complex moire pattern can be computed and stored as an image. The same operations can be performed with the deformed speckle pattern. The phase change due to displacement can be obtained by subtracting the phase map of the initial moire pattern from that of the final moire pattern. The software to implement this technique is under development.

11. <u>Contrast Enhancement using Binary Images</u>:

Under the circumstances where it is not possible to apply optical phase modulation, the contrast of the displacement fringes can be increased to some extent using binary speckle images. The initial speckle pattern and the deformed speckle pattern are transformed into binary images using a local threshold level for each pixel. The fringes are generated by the logical moire between the initial and deformed binary speckle images.

APPENDIX III

OVEN TESTS

OVEN MODIFICATIONS

The oven was modified from the previous experiment to allow for illumination in both horizontal and vertical directions. Figure 1 shows the previous door arrangement with three windows and an illumination angle of 45 degrees. Figure 2 shows the current configuration of five windows, two for horizontal illumination, two for vertical illumination, and one for observation. Because of vertical oven dimension limitations, the angle of illumination was changed to 30 degrees in both the vertical and horizontal directions.

The addition of two more illumination windows increased the air cavity in front of the sample. The thermal motion allowed by the increased cavity size necessitated the placement of a high temperature glass baffle between the sample and the cavity. This baffle reduced thermal motion sufficiently to allow the acquisition of the data used in the following sections.

Shadows from the loading mechanism appear at the top and bottom of the sample in the vertical illumination images. The top shadow is from the loading rod and stops the upper illumination beam; and the bottom shadow is from the base and stops the lower beam. Because there is only single illumination in each of these areas, strains in the shadow zones cannot be determined. The shadows do not affect the optical strain measurements at points not lying in the shadow zones.

Procedures

Figure 3 is a picture of the back of the sample used for this experiment. Five type K thermocouples are located at positions 1-5 indicated by dots in Figure 4. The four gauges are indicated by rectangles in Figure 4. For the low temperature (75-500 degrees F) test results for the WK gauges are presented.

A 16 input recorder was used to simultaneously record the five thermocouple temperatures at positions 1-5 respectively, strain gauges 1-4 at positions 6-9 respectively, and the oven thermocouple temperature was used as the reference temperature for all optical data. The gauge factor (GF) for each test of the strain gauge was calculated for the temperature at the thermocouple associated with each gauges, i.e., TC-1 temperature was used to calculate the GF of strain gauge 1 at each reference temperature where readings were taken.

The sample was then thermally cycled twice to 500 degrees F. After the second thermal cycle, the sample was mechanically cycled five times to approximately 6000 pounds load at the sample. Then the sample was thermally cycled a third time while apparent strains were recorded for each of the strain gauges.

Three complete temperature-load tests were then run. In the first, the Wheatstone Bridge circuits were zeroed at each temperature before each load cycle. In the second and third tests, the bridges were zeroed only at room temperature and the apparent strains due to thermal variation during the test were removed with data post-processing.

Optical Procedure

The sample was put under an initial load of 400 pounds gauge pressure. (Approximately 1600 pounds sample load). An initial image was acquired. The sample load was then increased until 6 fringes were observed. (6 fringes qualitatively determined to be the best contrast/load for processing). Another image was acquired at load. This process was repeated until approximately 6000 pounds sample load was achieved. This was done at each reference temperature and using both illuminations.

Gauge Results

The apparent strain data matched closely with the published curve from the gauges supplier. All three tests of the gauge produced effectively the same results. Figure 5 is a plot of oven temperature versus thermocouple temperature. There is a large gradient of temperatures between TC-1 and TC-3, this thermal gradient is corroborated by observation using the optical method during heating of the sample (thermal fringes show different fringe spacing in both areas).

Figures 6 and 7 are plots of the strain gauge data for gauges 3 and 4 respectively. The apparent slight increase in the modulus of elasticity before decreasing is repeated in all three tests.

Optical Results

The absolute value of the subtraction of any two consecutive images during a loading cycle produce a Moire image similar to Figures 8 and 9, horizontal and vertical illumination respectively. Line scans of the horizontal line through the center of Figure 8 and a vertical line through the center of Figure 9 are shown in Figures 10 and 11 respectively. In order to reduce the noise created by the speckle, but retain the Moire pattern, an elliptical passband filter in Fourier space was implemented. This filter applied to Figures 8 and 9 produced images in Figures 12 and 13 respectively; with line scans in Figures 14 and 15 respectively.

The line scans from each load at a given temperature are then processed to give the phase at every point along the line. The phases for each load are summed to help reduce thermal distortion, and the strains at each point are then calculated.

Tables 1 and 2 show the strains given by both the optical and gauge methods in the vertical and horizontal directions respectively, as well as the difference. The statistical analysis of this data shows that there is a .998 correlation between the two methods. Figures 16 and 17 are graphical depictions of tables 1 and 2.

Current Work

Thermal cycling is now under way for the high temperature version of this test.

Table 1.

Optical vs. Gauge			
4000 lb. load			
Vertical Strains & Illumination			
°F Temp. Oven	Gauge #3 Test II - Zero Wt.	Optical 4 Stage, Phase Avg.	% Difference Gauge - Optical
75	529 $\mu\epsilon$	501 $\mu\epsilon$	-5.3%
200	456 $\mu\epsilon$	477 $\mu\epsilon$	+4.6%
300	496 $\mu\epsilon$	525 $\mu\epsilon$	+5.7%
400	512 $\mu\epsilon$	487 $\mu\epsilon$	-4.8%
500	499 $\mu\epsilon$	507 $\mu\epsilon$	+1.6%

Table 2.

Optical vs. Gauge			
4704 lb. load Horizontal Illumination and Strains			
°F Temp. Oven	Gauge #3 Test II - Zero Wt.	Optical 4 Stage,Phase Avg.	% Difference Gauge - Optical
75	230 $\mu\epsilon$	243 $\mu\epsilon$	+5%
200	212 $\mu\epsilon$	227 $\mu\epsilon$	+6%
300	205 $\mu\epsilon$	221 $\mu\epsilon$	+7%
400	210 $\mu\epsilon$	211 $\mu\epsilon$	+0.8%
500	220 $\mu\epsilon$	216 $\mu\epsilon$	-1.5%

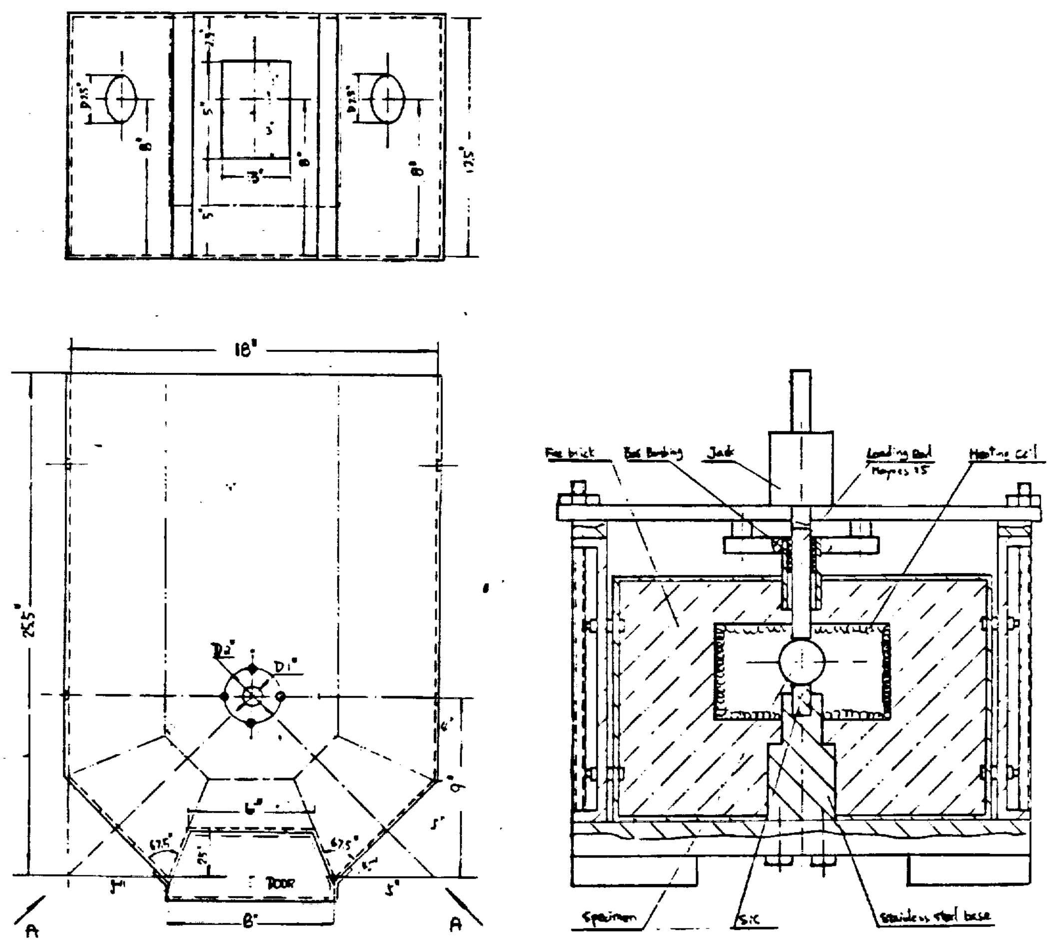


Figure 1. 3-Window Oven Diagram

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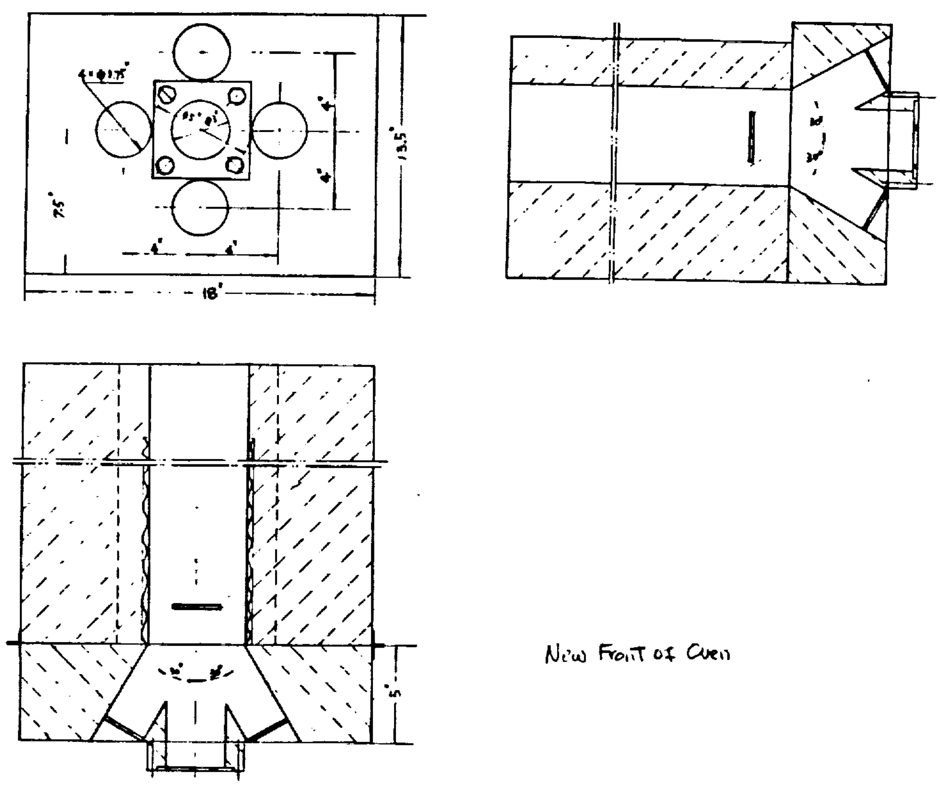

Figure 2. 5-Window Oven Diagram

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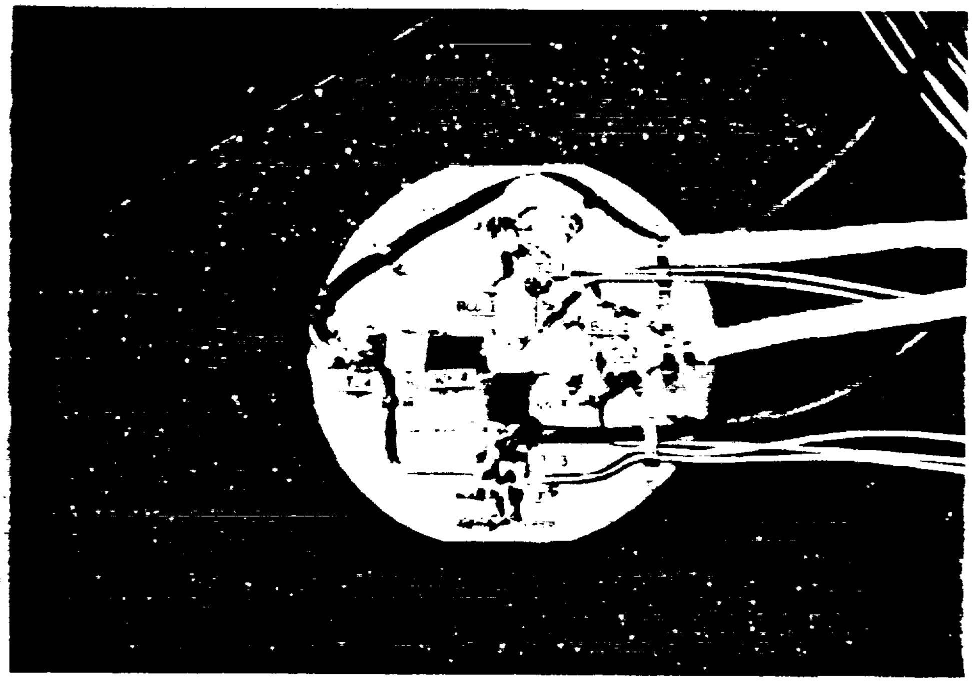

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Figure 3. Sample Back

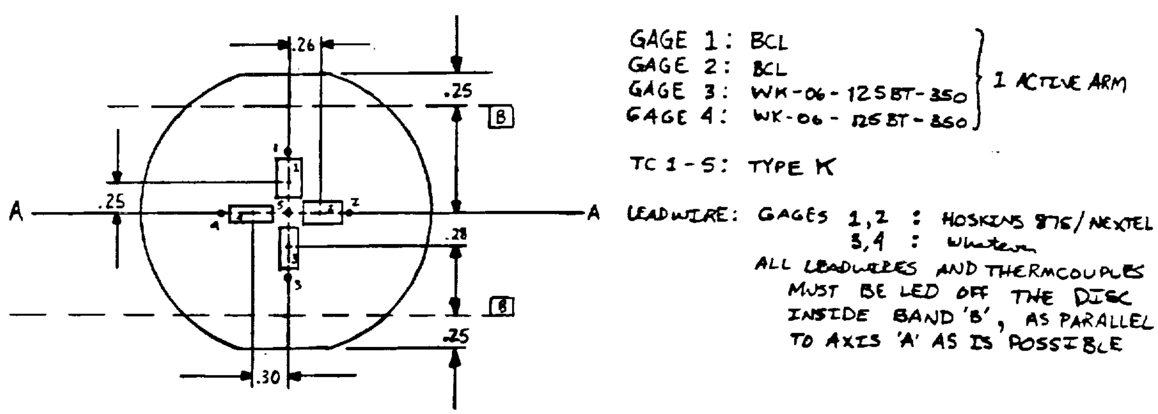


Figure 4. Sample Sensor Arrangement

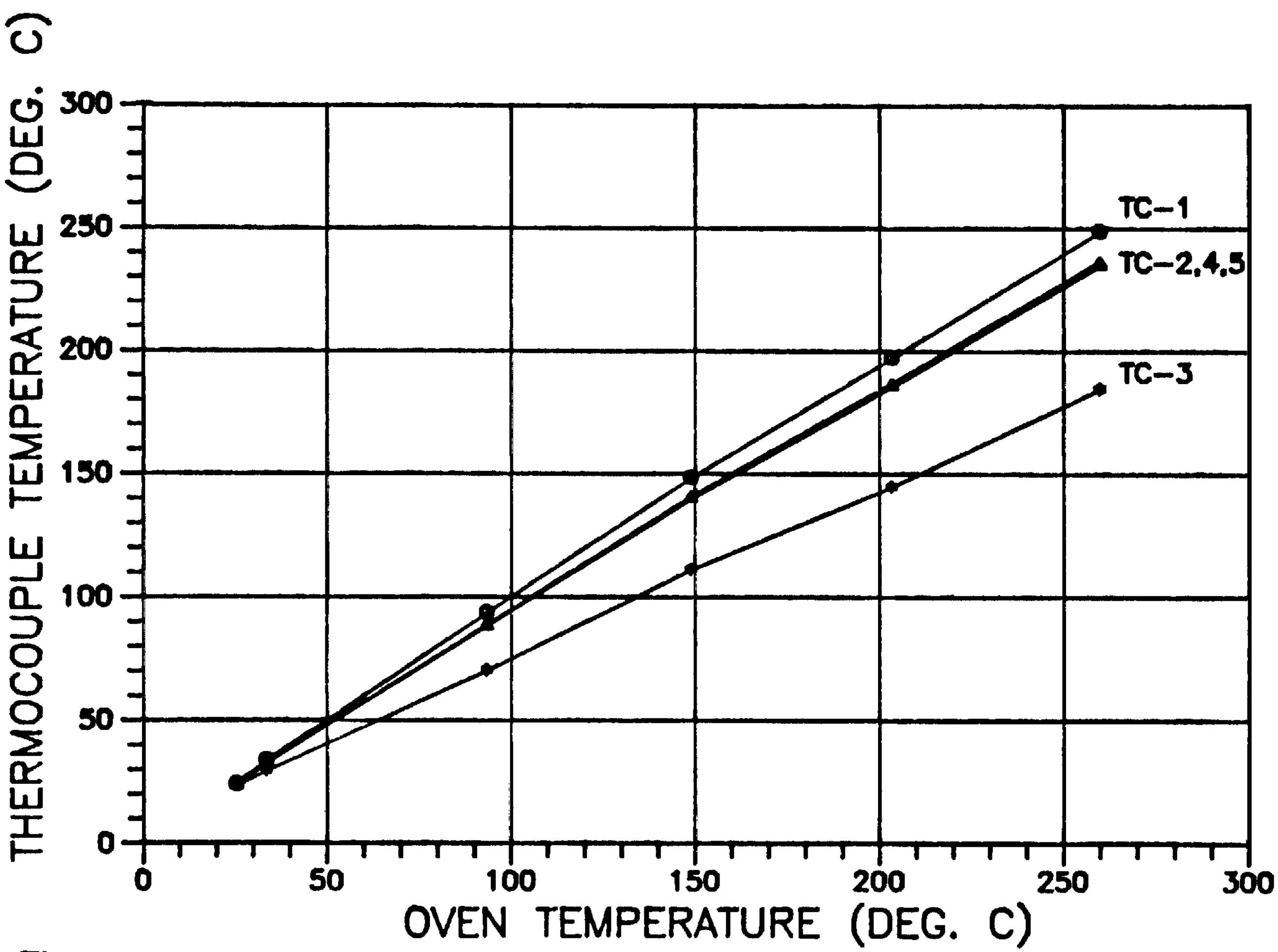


Figure 5. Plot of Oven Temperature versus Sample Temperature at the five thermocouple positions

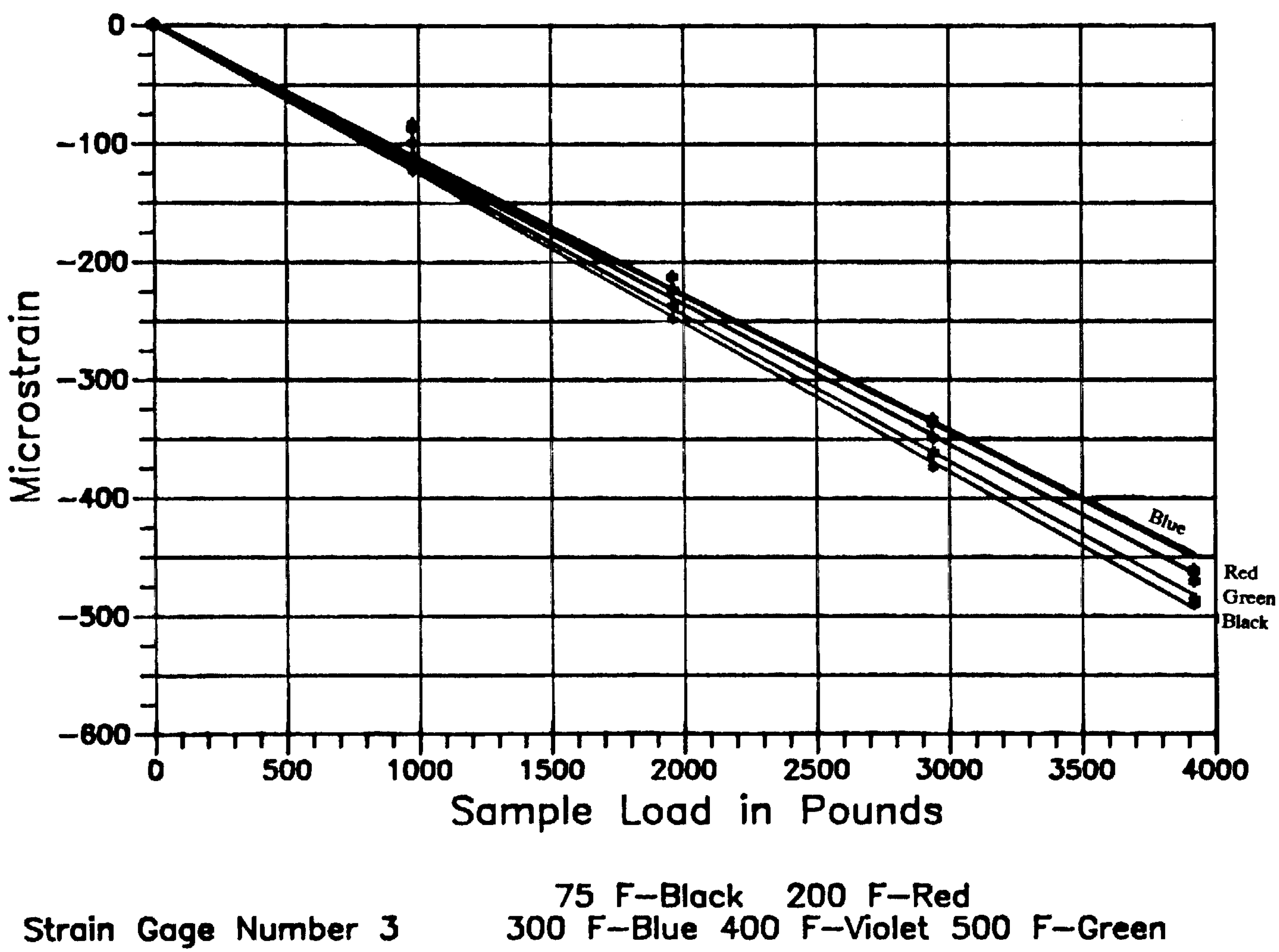
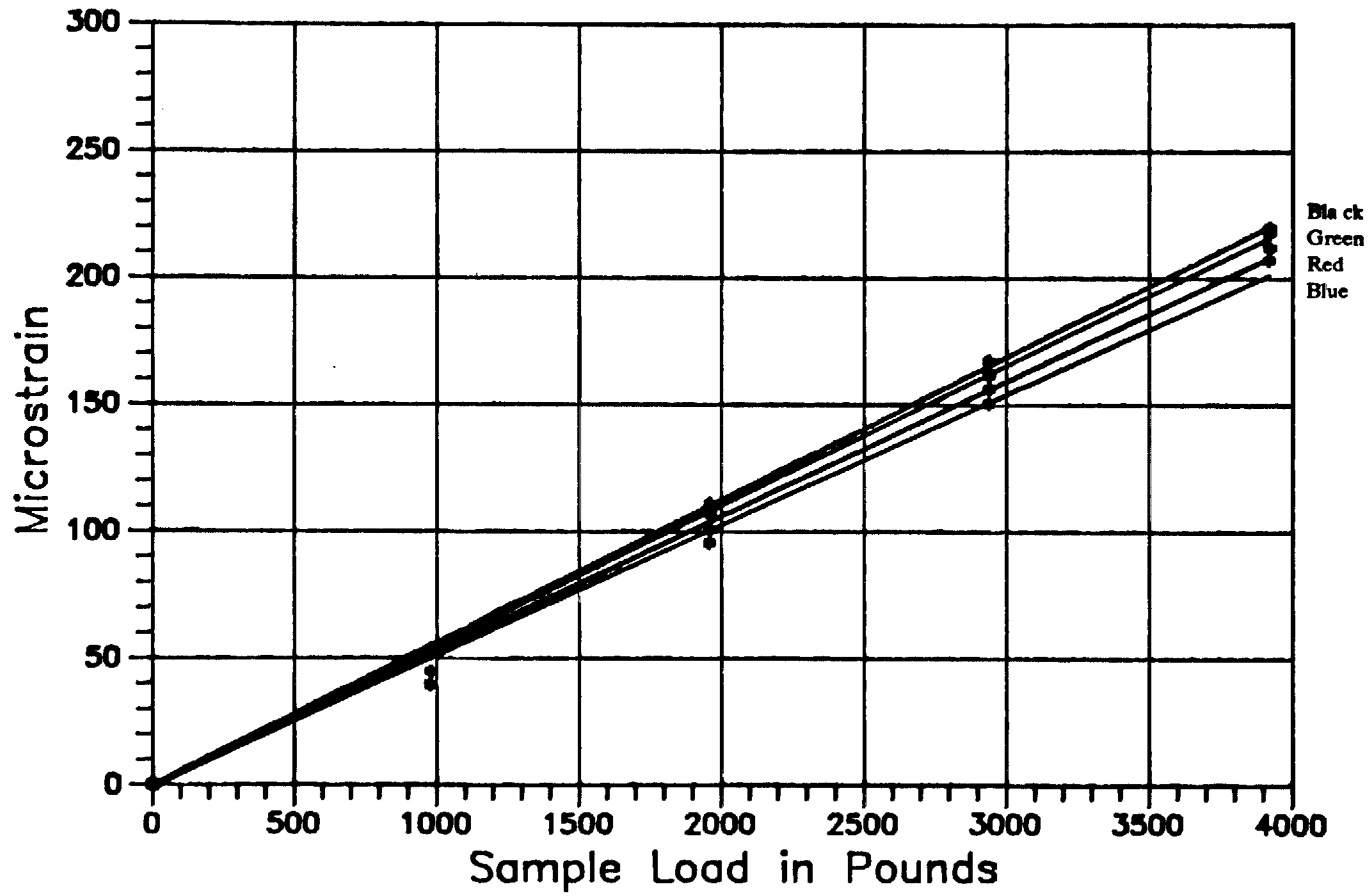

0
-100
-200
-300
-400
-500
-600
Microstrain
0
500
1000
1500
2000
2500
3000
3500
4000
Sample Load in Pounds
Blue
Red
Green
Black
Strain Gage Number 3
75 F—Black 200 F—Red
300 F—Blue 400 F—Violet 500 F—Green

Figure 6.



Strain Gage Number 4

75 F–Black 200 F–Red
300 F–Blue 400 F–Violet 500 F–Green

Figure 7.

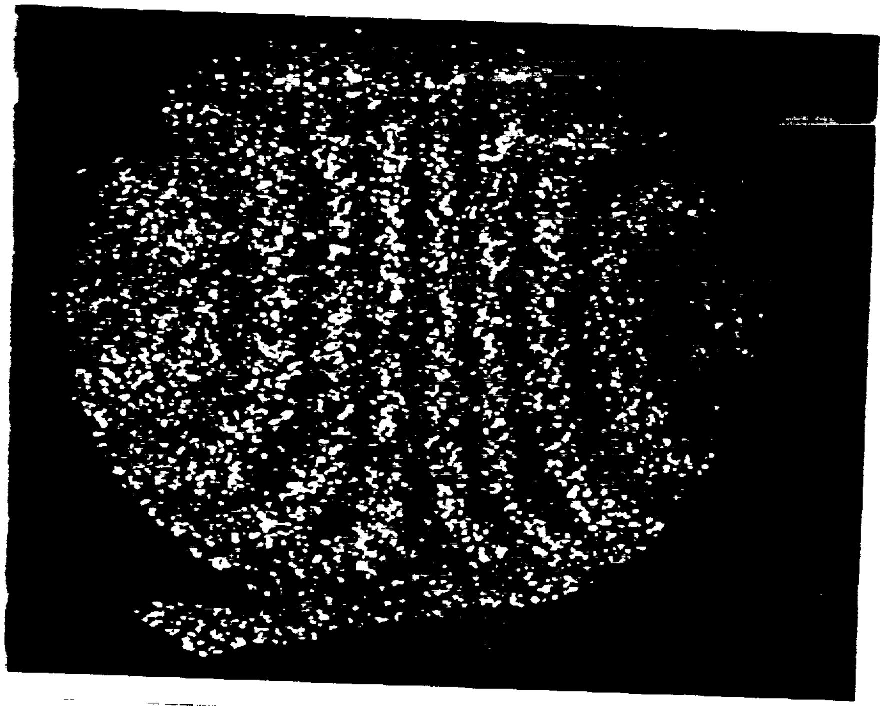


Figure 8. Horizontal Illumination

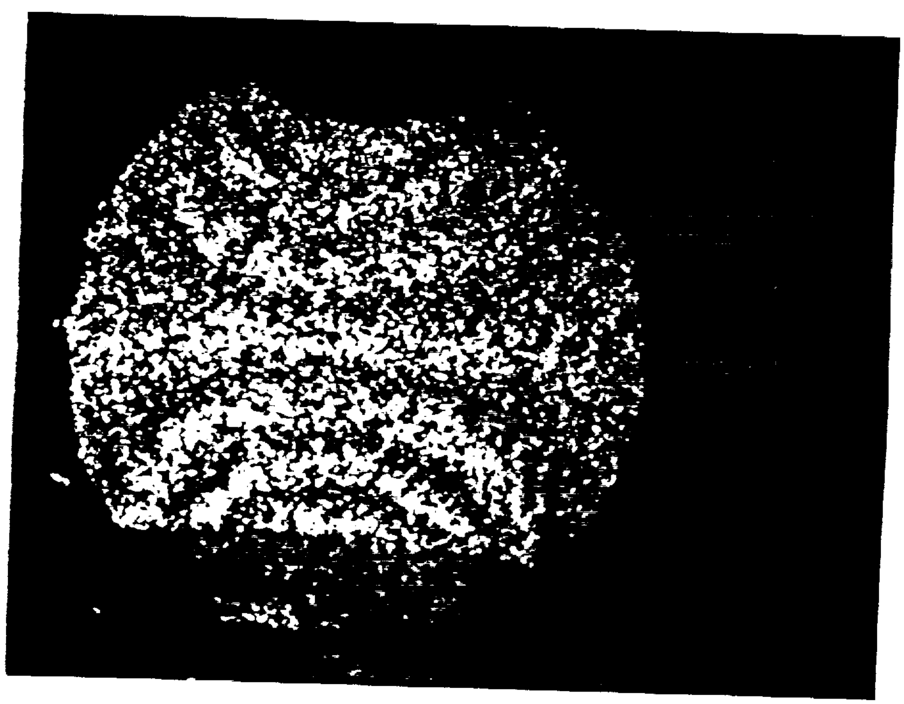


Figure 9. Vertical Illumination

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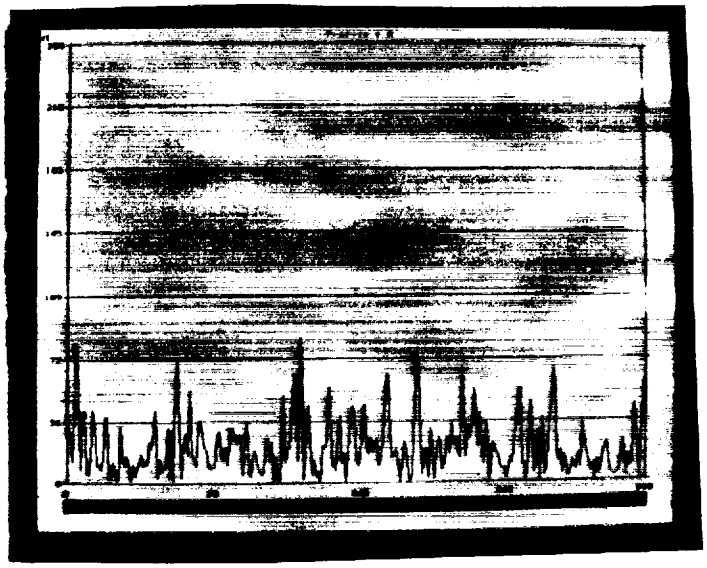

Figure 10. Horizontal Line

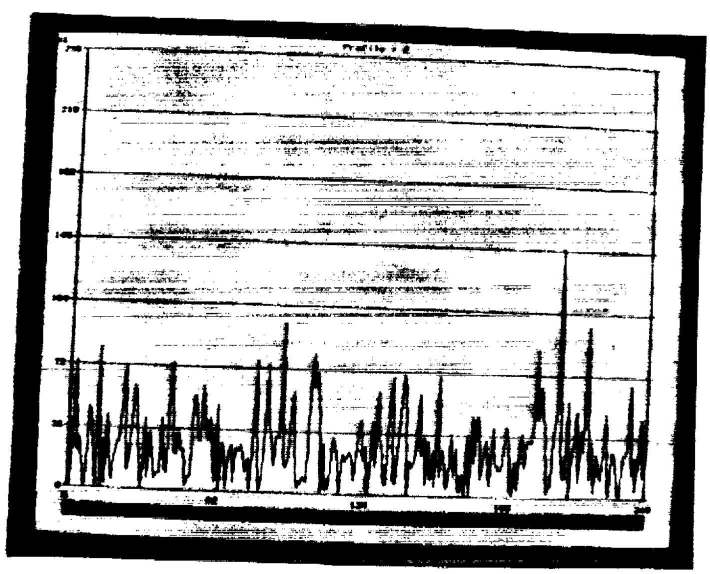

Figure 11. Vertical Line

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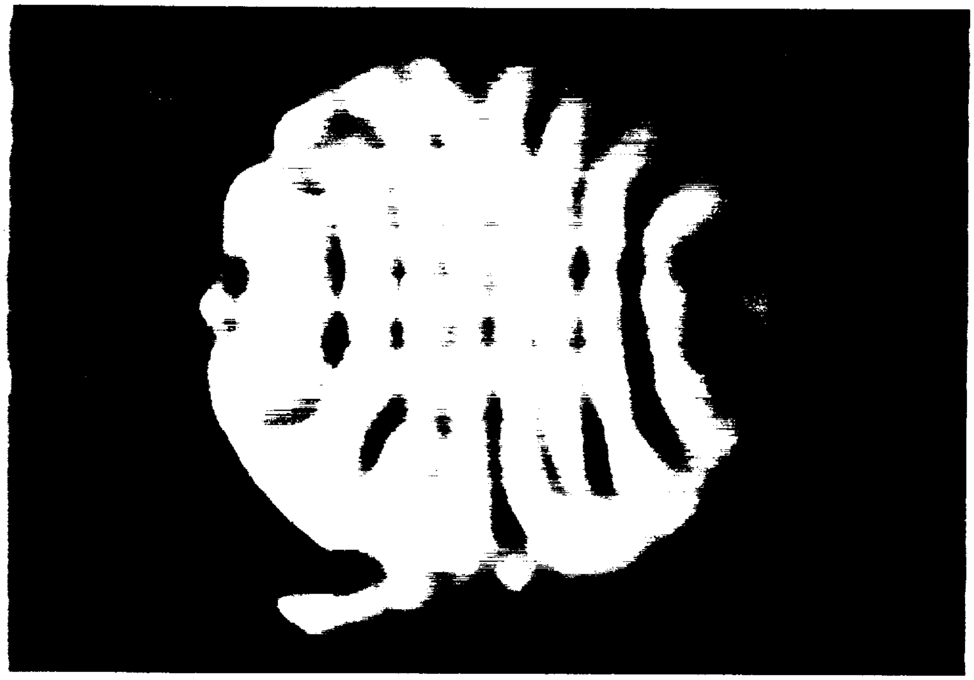

Figure 12. Horizontal Filtered

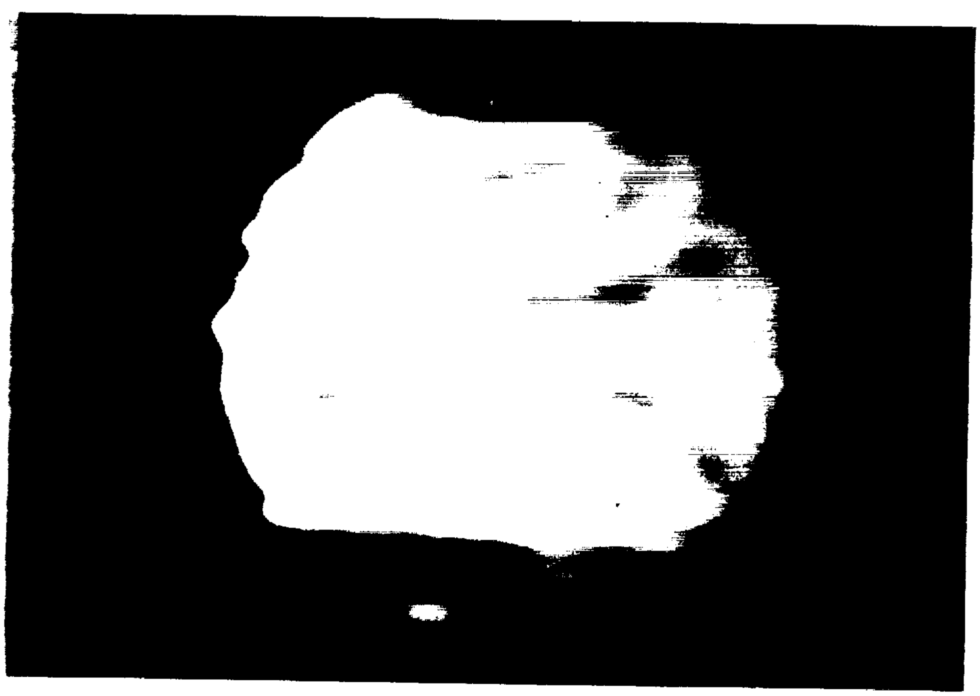

Figure 13. Vertical Filtered

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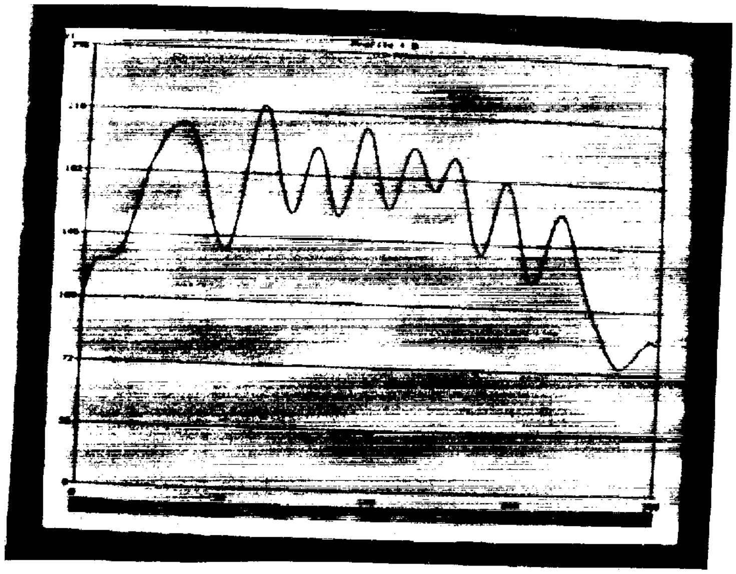

Figure 14.

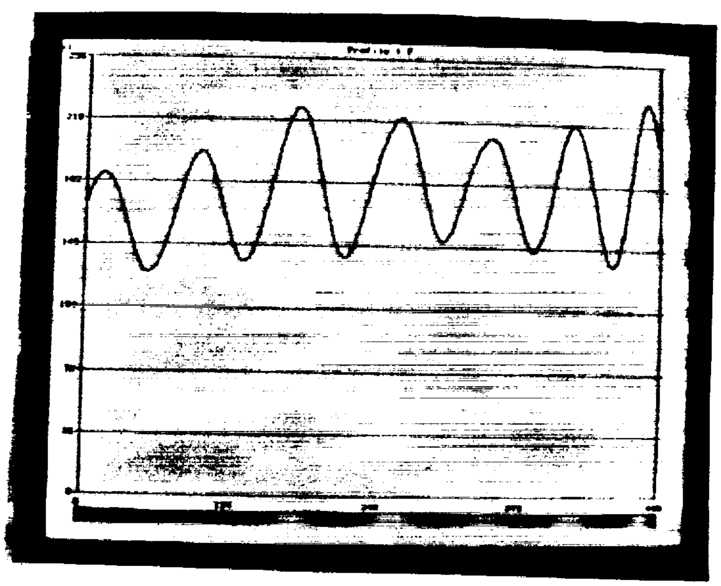

Figure 15.

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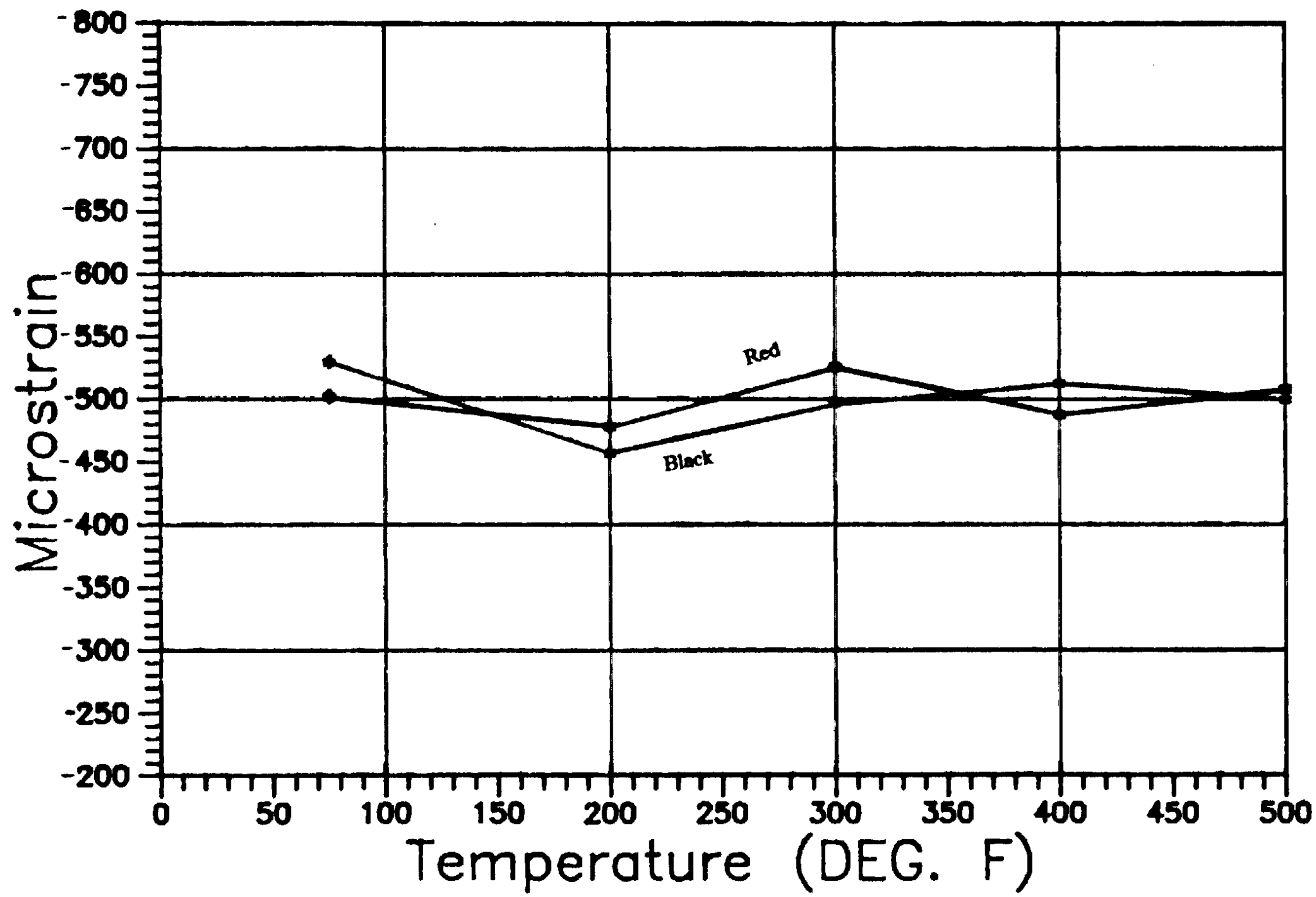

Figure 16. Plot of Optical and Gage Data versus Temperature
Black—Gage 3 Red—Optical
Vertical Illumination and Strains

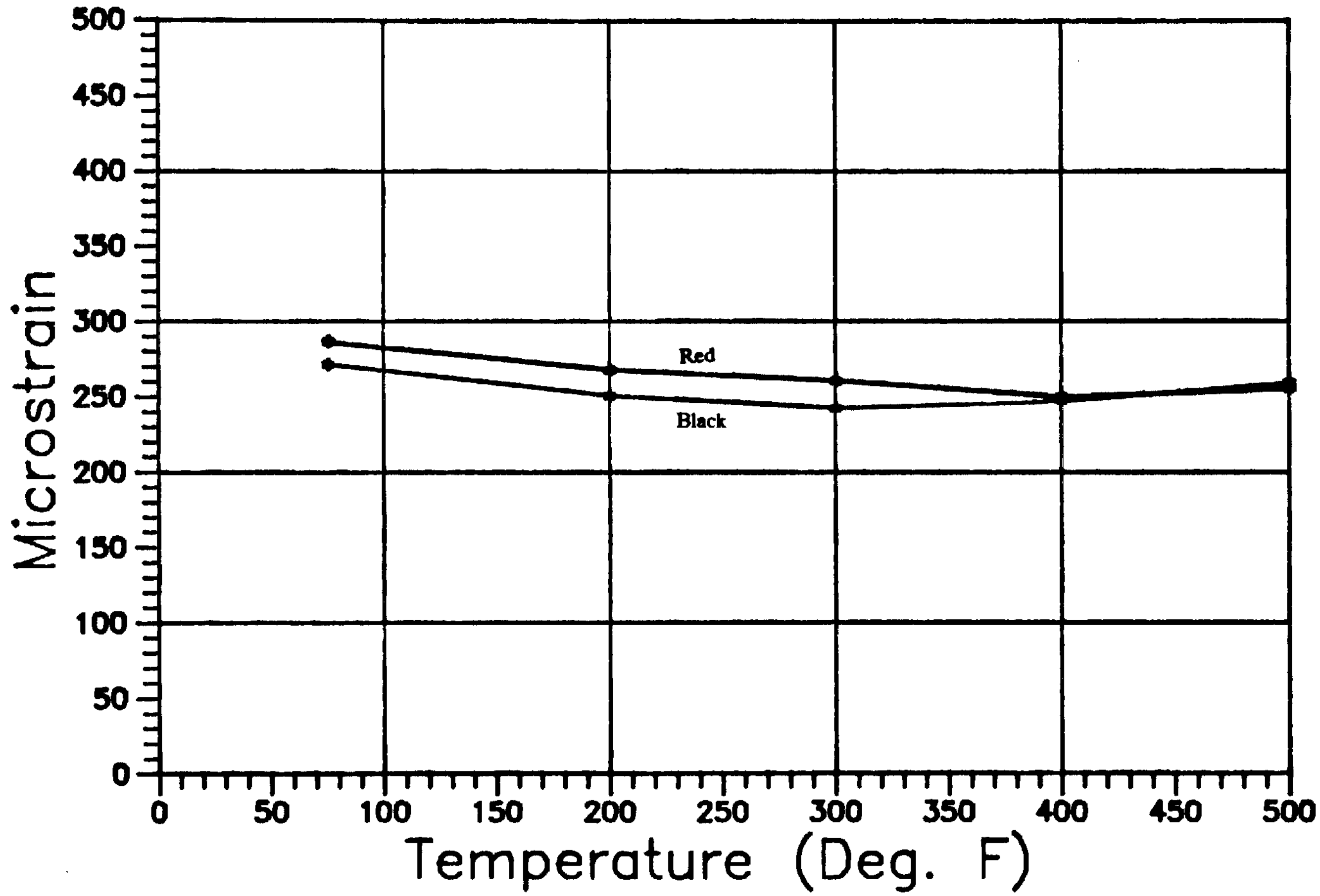

Figure 17. **Plot of Optical and Gage Data versus Temperature**
Black—Gage 4 Red—Optical
Horizontal Illumination and Strains