Non-contract surface flaw inspection a study of the use of retroreflection for qualitative and quantitative evaluation of static and dynamic surfaces.

Cameron A. Montrose
University of Windsor

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NON-CONTACT SURFACE FLAW INSPECTION

A STUDY OF THE USE OF RETROREFLECTION FOR QUALITATIVE AND
QUANTITATIVE EVALUATION OF STATIC AND DYNAMIC SURFACES

A Thesis Submitted to the
Faculty of Graduate Studies and Research
through the Department of
Mechanical Engineering in Partial Fulfillment
of the Requirements for the Degree of
Master of Applied Science at the
University of Windsor

By

Cameron A. Montrose

Windsor, Ontario
1988
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ISBN 0-315-43762-6
SUMMARY

The primary purpose of this study was to experimentally determine if the retroreflected primary image of a reflective surface could be used for static and dynamic contour measurements. The work was divided up into two experiments:

Experiment 1 - Establish a correlation between a known static surface contour and the grey levels of its retroreflected image.

Experiment 2 - Determine if the modal shapes in a vibrating (dynamic) surface may be detected using retroreflection.

The first experiment examined a 1-D concave contour on a reflective panel of stainless steel. The contour ratio, i.e., the width/depth ratio of the contour, was adjusted in intensity using air pressure. For various contour ratios, the retroreflected image was converted into grey levels and analyzed using a solid state camera interfaced with a microcomputer. The actual shape of the contours were measured using an LVDT. Non-dimensional plots were used to establish correlations between the measured grey level, the first integral and second integral of the grey level, and the actual shape of the contour. Experiment 1 found that the primary retroreflected image is proportional to the average of the complement of the panel contour and the 2nd derivative of the surface contour. Images were evaluated for contour ratios between 0.00083 and 0.0023. The accuracy of this correlation, based on the non-dimensional results is about 17%, with a repeatability of 18%.
The second experiment examined the retroreflected images seen on a thin, square, reflective brass plate. The plate was clamped along all edges and acoustically excited to stable harmonics which produced linear, parallel nodes. Eight modal shapes in the plate were examined for frequencies ranging from 120 to 1550 Hz. The images were best seen using a stroboscopic lamp. The dynamic retroreflected images resembled several static contour images side by side. This was attributed to the retroreflection phenomenon displaying concave contours better than convex contours. It was observed that modal shapes which had an odd number of nodes yielded particularly good images. It was established that the high intensity regions, seen using quasi-on-axis retroreflection, were located at the concave anti-nodes in the plate surface.

The first experiment did not examine convex contours because it was assumed that they yielded primary images equal and opposite to the concave contours. The dynamic analysis showed that retroreflection displays concave contours better than convex. Therefore experiment 1 should be repeated for convex contours. This will not be difficult to do since the equipment and method developed in experiment 1 may be used again.

The results from this study proved that retroreflection can be a very useful tool for both quantitative measurements and qualitative contour imaging of static and dynamic surfaces.
ACKNOWLEDGMENTS

The author would like to express his sincere gratitude to Dr. W.P.T. North for his supervision and encouragement throughout the course of this study, as well as to Dr. V.M. Huynh and Dr. A.C. Smith for their valuable guidance as committee members. The author also wishes to thank Dr. R.G.S. Gaspar for his assistance in the field of photography and R.L. Reynolds for helping the author understand the phenomenon of retroreflection.

A special thanks must be given to Mr. W. Beck, Mr. R. Tattersall of the ME department, and Mr. D. Liebsch of the Central Research Shop for their technical assistance in this project. The author is grateful to Mr. and Mrs. R.G. Montrose and Miss E.A. Noble for assisting in the preparation of this manuscript.

This project was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through Grant No. 9067.
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NOMENCLATURE

1st Integ. - 1st integral of the direct intensity, normalized.

2nd Integ. - 2nd integral of the direct intensity, normalized.

Contour Ratio - Wmin/Xcontour, abbreviated as W/X

Imax - the maximum grey level value of intensity in a retroreflected image.

Imin - the minimum grey level value of intensity in a retroreflected image.

I(x) - the grey level value of intensity in a reflex reflected image at a given location x.

mode(m,n) - mode of vibration:
m node lines along the x axis
n node lines along the y axis
(each edge counts for 1/2 a node line)

Normalized Contour Height - \[ \frac{W(x) - W_{\text{min}}}{W_{\text{max}} - W_{\text{min}}} \], abbreviated N.C.H.

Normalized Intensity - \[ \frac{I(x) - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} \], referred to in an abbreviated form N.I.

Normalized Position - \[ \frac{x}{X_{\text{max}}} \]

Wmax - the maximum contour height for a surface being analyzed.

Wmin - the minimum contour height for a surface being analyzed (maximum depth).

W(x) - the depth of the contour at a distance x from the edge of the region being examined.

x, X - the position from the left edge of the retroreflected image of a flaw being examined. The contour of the flaw varies along the x axis.

Xcontour - the width of the contour being examined.

Xmax - the width of the region being examined.
1. INTRODUCTION

1.1 Retroreflection for Quality Control

Quality control is one of the most important areas of today's manufacturing. Fierce competition has forced some manufacturers to invest millions of dollars in modern technology in order to improve their standards of quality. Automobile manufacturing is a well-known example of an industry which has had to make improvements in quality control.

One area of quality control which requires improvement is the static inspection of frame and sheet metal work. Full field sheet metal inspection still employs methods used years ago, such as examining the reflection of a set of light and dark stripes off a reflective sheet metal surface [15]. This method only detects flaws in the regions where the reflection of the interface between the light and dark stripes occur. As well, if the ideal specimen has a shape to it, the inspector must remember what the ideal reflection pattern looks like and compare it to the specimen being presently inspected. Such difficulties can make the inspection process subjective. The facilities required for such inspection can be expensive to construct.

Another area of interest in quality control is inspecting the dynamic behaviour of a sheet of material. An example where this type of inspection is important is the detection of debonding in composite sections. Holography, speckle and moire interferometry methods are presently used.
to determine the modal shapes of vibrating surfaces. Although these methods of inspection are highly accurate, they are time consuming, i.e. 100% inspection of production capacity can be very difficult to achieve, extremely expensive to implement and require strictly controlled environmental conditions in order to successfully use them.

A totally new method of full field surface inspection is proposed which requires only a retroreflective, or 'reflex' screen, a reflective specimen and a source of light. It is inexpensive, easy to implement, and provides a continuous full field view of the surface. By reflecting light off the inspected surface onto a retroreflective screen and viewing the image on the retroreflective screen from the reflective surface, local minute imperfections in the surface become quite visible in the form of accentuated grey levels. Not only are minute dents visible, but it is possible to determine if they are indents or outdents. This method is relatively cheap, easy to install in a factory environment and requires only white light.

1.2 The Concept of Retroreflection

A retroreflector is a device that reflects light back in the same direction (or close to it) as the incident light beam, or source [1], shown in Figure 1-1. The characteristic of such a reflector in returning light back to the source of an angularly incident beam of light, gives rise to the term "reflex" reflector. A reflex reflector is
different from a mirror which causes specular reflection and from diffusing types of reflective surfaces which dissipate the incident light in all directions without a selective return in the direction of incidence [3]. Retroreflection has been used in many applications, such as traffic signs and highway pavement markings, because of its ability to return a large quantity of light back in the same direction from which it originated [1][3].

Most retroreflectors consist of tiny glass beads of high refractive index laid upon a reflective backing, as shown in Figures 1-2a&b [2]. Figure 1-3a [1] depicts how retroreflection occurs: upon entering the bead, the light experiences refraction and reflection and leaves in approximately the same direction it entered. Note however, that the angle delta of the ray leaving the bead depends on the angle, alpha of the incident ray and the index of refraction of the bead, n, shown in Figure 1-3b [1]. Thus if a bundle of rays strike the surface of the bead, the reflected rays will leave in a diverging cone of light. It is the imperfectly retroreflected diverging rays of light which makes flaw detection possible.

1.3 Reflex Reflection for Contour Visualization

The basic setup required for viewing a surface contour using retroreflection is depicted in Figure 1-4. A light source is aimed so that it emits a uniform light field onto the reflective surface, which will reflect this light onto
Figure 1-1 A retroreflected ray of light

Figure 1-2 a) Cross section of a glass bead retroreflector
b) Actual photograph of a glass bead retroreflector (mag. 75 x)
Figure 1-3  

a) Ray path showing retroreflection in a glass bead  
b) Graph showing relationship between $\alpha$, $\delta$ and $n$.  

---  

Figure 1-4  Basic setup for surface inspection using retroreflection
the reflex screen. If any local irregularities exist in the surface, the uniform light field upon striking the surface of the specimen will become distorted, and the light field will now have varying grey levels upon striking the retroreflective screen. If the reflex reflecting material retroreflected light perfectly, each ray of light would follow the exact same path along the optical axis back to the light source. Furthermore, upon being re-reflected back from the specimen surface, all the distortions occurring to the light field from the first reflection will simply be reversed, i.e., a uniform light field will return to the source. However, for an imperfect retroreflector, such as the glass bead type, the rays in the diverging cone of light will not trace their incident path back to the reflex reflector. If a different path is followed, then the rays in the diverging cone of light will not reflect from the specimen at the exact same point they did the first time, thus not eliminating (reversing) the distortions in the light intensity field that occurred from the first reflection. Since the rays in this diverging cone do not return to the light source, they may be detected by an outside source, such as a camera, or human eye.

The imperfectly retroreflected light actually creates two types of phenomena for surface contour visualization. The first effect, the primary signature, is the reflected image seen in the panel of the distorted light field on the retroreflective, or retro, screen. This image will move if the viewer changes position with respect to the light
source. Preliminary work by the author using retroreflection for imaging dents in automobile hoods suggested that the intensity or grey level pattern is proportional to the slope or rate of change of slope of the contour of the dent. It is these observations which formed the hypothesis of the research.

The secondary signature effect is created by the shadows of the contour on the panel surface cast by the reflex reflected light from the retro screen. This is simply a backlighting effect which may be seen by viewing the surface opposite to any light source such as a window [17].

Contour visualization using retroreflection is dependent upon the following geometric variables [18], shown in Figure 1.4:

i. The angle between the inspected surface and the light source.

The smaller angle the angle $\alpha$, the greater the reflectivity, parallax distortion (a distortion occurs if one region of the panel is significantly closer to the viewer than another), and secondary signature image. The secondary signature is an effect not unique to retroreflection and therefore was not examined. In order to separate the latter two effects from the primary image, angle $\alpha$ was made as large as possible. No change in the primary image was observed when angle $\alpha$ is varied, other than being uniformly expanded or compressed.
ii. The angle between the retroreflective screen and the reflected light rays from the surface being inspected.

Light rays striking the reflex screen at a very small angle, b, will be retroreflected poorly. It is desirable to have angle b about 90 degrees, though preliminary work showed angle b could be as small as 45 degrees without affecting the quality of the retroreflected image.

iii. The illumination source - viewer distance.

The farther away the viewer is from the light source, distance c, the lower the overall intensity of the contour image. The location of the light source is important since it can create two types of images of a contour - an on-axis and off-axis image. These images are discussed in section 3.1.2.2.2.

iv. Size of the illumination source.

The sensitivity of retroreflection for contour visualization is inversely proportional to the size of the illumination source, d. In order to obtain the highest resolution possible using retroreflection, the smallest light source possible was used.

v. The surface to retroreflective screen distance.

As the panel-retro. screen distance, e, increases, a higher percentage of light rays will not re-reflect off the exact same surface locations. As a result, more light which contains distortion information will reach the viewer. Distance e was kept as large as possible.
2. LITERATURE SURVEY AND OBJECTIVES

2.1 Literature Survey

Most of the information about retroreflectors has been developed for traffic purposes. Stoudt and Vedam [1] have performed ray tracing studies on spherical reflex reflecting materials in order to optimize the off-axis retroreflection of pavement markers. Their work provides useful information concerning the behavior of light for both specular and diffuse reflection of light through glass beads. Venable et al [4]—have experimentally measured the intensity of retroreflected light for various off-axis locations for glass bead and prism reflex reflecting materials and their results suggest the former gave a wider intensity distribution. For our purposes this is desirable and establishes the use of spherical beaded retroreflectors for this study. Havens and Peed [5] used geometric optics to determine the behavior of light in a glass bead retroreflector. Their paper explains the optical phenomenon of glass bead retroreflection. Additional work has been done for C.I.E. photometric information [6],[7],[8],[9].

Most of the information concerning the construction of glass bead retroreflectors is from the patents such as those filed by Gill [10], Palmquist [11], and McKenzie [12]. Their patents are variations on the design of the glass bead retroreflector. West and Barker [13] patented the use of retroreflection in a form of optical triangulation arrangement for inspecting optical surfaces. Genco and Task
patented the use of retroreflection for inspection of surface flaws and birefringence in transparent materials [14]. Clarke, Reynolds, and Pryor [15] have patented the use of retroreflection for opaque surface panel inspection, applicable for inspection of materials such as sheet metal and plastic.

2.2 Objectives of Research

Retroreflection appears quite promising as a tool for full field surface inspection. The objective of the work presented in this paper is to appraise retroreflection as a new method of non-contact inspection of static and dynamic surfaces by addressing the following questions:

i. What is the resolution, accuracy and precision of retroreflection for surface contour measurements?

ii. Is the intensity pattern seen using retroreflection related to the contour, slope of contour, or rate of change of the slope of the contour?

iii. Can this method be used for inspecting both static and dynamic surfaces?

iv. How may the shades be quantitatively analyzed?

These questions are answered from the results of the following two experiments:

Experiment 1 - Establish a correlation between a known static surface contour and a retroreflected grey level image.

Experiment 2 - Determine if modal shapes in a vibrating (dynamic) surface may be detected using retroreflection.
3. EXPERIMENTAL WORK

3.1 Experiment 1 - Static Analysis of A One-Dimensional Surface Contour Using Retroreflection

3.1.1 Purpose

The purpose of the experiment is to determine if the primary signature from a reflex reflected grey level image of a static surface can be related to its contour, its slope, or rate of change of slope of its contour. The resolution, sensitivity and accuracy of this method are established from the results.

3.1.2 Experiment Design

The contour is generated by using a vacuum to suck a long, concave contour into a flat panel of reflective sheet metal. The retroreflective image is captured using a CCD camera and analyzed using image processing software on a microcomputer. The actual shape of the contour is established using a LVDT.

3.1.2.1 Generating a 1-D Surface Contour

In order to simplify the contour analysis, the ideal surface profile should be continuous, one-dimensional and symmetrical about its centre line. Profiles of similar shape but variable degree of intensity should be examined in order to establish the minimum contour ratio (depth/width) required for detection. The surface of the panel should be specularly reflective and have no other
contours than the one examined.

The material chosen for the analysis is 0.0508 mm (0.020") thick type 403 Stainless Steel sheet with an XL-buff finish, which gives a mirror-like appearance. The concave contour was generated using a contour generator, shown in Figure 3-1. A sheet panel was placed over a plate of aluminum with a long narrow trench cut into it. The two pieces were sealed together using a fillet of silicon sealant around their interface. The opposite side of the plate had a valve stem inserted so the air in the trench may be removed using a vacuum hand pump. The depth of the concave contour in the sheet metal is controlled by the vacuum. This method of concave contour generation was chosen because:

i. The contour is continuous, symmetrical and, in the central region of the trench, the profile is one-dimensional.

ii. The metal is very stiff, the surface easily scratched, and in limited supply. More time and material would be consumed generating profiles of similar quality via inelastic distortion of the metal.

It is assumed that convex and concave contours of equal contour ratios will produce equal but opposite primary signature intensity patterns.
Figure 3-1 Contour generator
3.1.2.2 Arrangement of Equipment

3.1.2.2.1 Viewer/Panel Angle

In order to eliminate secondary signature effects, parallax distortions and to maximize the width of the image seen in the panel, it is necessary to view the surface as close as possible to its normal, without reflecting the light source back to the viewer.

3.1.2.2.2 On-Axis and Off-Axis Viewing

The retroreflected image of a surface contour will vary depending on the position of the viewer and the light source. Figure 3-2b shows an unsymmetrical retroreflected image of a surface contour created when the light source is off-set from the optical axis of camera lens, shown in Figure 3-2a. Unsymmetrical images are referred to as off-axis in this paper. Figure 3-2d shows a symmetrical image of the symmetrical contour created when the light source is on the optical axis of the camera lens, shown in Figure 3-2c. This symmetrical reflex reflected image is referred to as an on-axis image.
Figure 3-2  a) Off-axis positioning of camera and light source
b) Off-axis retroreflected image of panel

c) On-axis positioning of camera and light source
d) On-axis retroreflected image of panel
3.1.2.3 **System Variables (Dimensional Analysis)**

Relationships between the surface contour and the grey levels of a retroreflected image are best recognized using non-dimensional variables. If a grey level value, $I(x)$, at a location $x$, is normalized between the maximum and minimum measured grey levels, $I_{\text{max}}$ and $I_{\text{min}}$ respectively, intensity variations because of light source intensities, camera aperture stops and viewing geometry are eliminated. If the height of the contour, $W(x)$, at a location, $x$, within a region of a certain width, $X_{\text{max}}$, is normalized between the range of maximum and minimum measured contour heights, $W_{\text{max}}$ and $W_{\text{min}}$ respectively, then only relative changes in the shape of the contour matter. Note that $W_{\text{min}}$ is the maximum depth of the contour and that the width of the region being inspected, $X_{\text{max}}$, usually is greater than the width of the contour, $X_{\text{contour}}$.

The normalized intensity, (N.I.), normalized contour height, normalized distance and contour ratio are defined respectively as:

\[
\frac{I(x) - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} \quad \frac{W(x) - W_{\text{min}}}{W_{\text{max}} - W_{\text{min}}} \quad \frac{x}{X_{\text{max}}} \quad \frac{W_{\text{min}}}{X_{\text{contour}}}
\]

3.1.2.4 **Image Processing Programs**

The retroreflected image was analyzed using the image processing computer programs INT_MAIN and INTEGRAL. These programs were designed to operate on an IBM AT with a Matrox PIP-1024 image processing board. This hardware
allows an image to be read from a file or CCD camera. Pixel intensities are converted to grey level values ranging from \( \frac{1}{2} \) to 256 and can be processed using a set of software commands which may be implemented in a FORTRAN or C written program.

3.1.2.4.1 PROGRAM 1: INT MAIN

INT_MAIN evaluates the retroreflected image of a surface contour in the following manner:

i. Obtain an image and select the region to analyze

   This program allows the user to analyze an image directly from a CCD camera or a previously stored image file on a floppy or hard disk. Once the image is loaded, a region is squared off and analyzed.

ii. Determine average grey level for each pixel along x axis

   The central region of the concave contour is one dimensional, thus a region only one pixel high and Xmax wide need be examined. A more typical value of the intensity at location \( x \) is obtained by averaging the grey levels of the pixels perpendicular to the \( x \) axis for each point within the boundaries set in the squared off region. INT_MAIN can analyze 1-D contours oriented horizontally or vertically.

iii. Write grey levels to a file

   After the average grey level for each pixel along the \( x \) axis is evaluated, the program will store either the grey
levels directly or normalized. A FORTRAN listing for this program may be found in Appendix I.

3.1.2.4.2 Program 2: INTEGRAL

In order to compare the normalized nth derivative of the contour with the normalized intensity, the grey levels are integrated n times, normalized and compared directly to the normalized contour, i.e.,

\[ \frac{d^n w(x)}{dx^n} \propto I(x) \quad \Rightarrow \quad w(x) \propto \int^n I(x) \, dx^n \]

This approach was used because there were more grey level points (approx. 350) than contour measurements (72 points), thus less error integrating the intensity n times than taking n derivatives of the contour data. INTEGRAL integrates and normalizes the grey levels in a flaw in the following manner:

1. Read grey level values from a file

The normalized or actual average grey levels measured and stored in a file by INT_MAIN are read. Normalized values are successfully plotted for the user.

2. Integrate read in grey level values

The N grey levels are integrated by summing up rectangles of area \((\text{grey level} - \text{zero}) \times 1/N\). The grey level zero is required for proper integration, as shown in Figure 3-3a. Areas calculated for grey levels lower than zero are negative and above, positive. The value of zero is found knowing the location where the integral is zero.
Figure 3-3 Integration of plot a to obtain plot b
For example, consider comparing the normalized slope of a surface contour to the grey levels of a retroreflected image. The normalized intensity will be integrated once, re-normalized and compared with the normalized contour profile. In order to integrate the intensity pattern, INTEGRAL must know where the value of the integral is zero. The user must enter a location, x, where the contour is zero (any non-zero contour value would require knowledge of the unknown proportionality factor), shown in Figure 3-3b. In experiment 1 the contour height along the outer boundaries of the region being examined is considered zero. INTEGRAL then uses an iterative algorithm to determine the grey level, zero, for which,

\[ \sum_{i=1}^{x} \frac{[\text{GREY LEVEL}(i) - \text{ZERO}] \times 1/N}{i} = 0 \]

iii. Store integrated values

When zero is determined and the whole region is integrated, the values may be stored in a file as is or normalized. The user has the option of repeating the integration on the new values. A FORTRAN listing for this program may be found in Appendix I.
3.1.3 Equipment

The following equipment was used in this experiment:

<table>
<thead>
<tr>
<th>QTY</th>
<th>DESCRIPTION</th>
<th>I.D. NO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IBM-AT w/ PIP 1024 image-processing board and INT_MAIN and INTEGRAL software</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>solid state camera (RCA CCD TC 2811)</td>
<td>213229</td>
</tr>
<tr>
<td>1</td>
<td>coaxial T fitting</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>fiber optic light source (Cuda model 1-150)</td>
<td>113037</td>
</tr>
<tr>
<td>1</td>
<td>B&amp;W T.V. monitor (Electrohome)</td>
<td>127071</td>
</tr>
<tr>
<td>1</td>
<td>colour T.V. monitor connected to the IBM-AT (NEC multisync colour monitor)</td>
<td>119525</td>
</tr>
<tr>
<td>1</td>
<td>mobile cart (Mat-Han-Quip Ltd.)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>magnetic base for holding fibre optic cable</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20' 3-prong polarized extension cord.</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.5&quot; width contour generator</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>U-tube manometer (Hg filled) w/ hand vacuum pump, plastic tubing w/ clamp</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1-D linear traverse w/ servo motor</td>
<td>33254</td>
</tr>
<tr>
<td>1</td>
<td>traverse power supply</td>
<td>33255</td>
</tr>
<tr>
<td>1</td>
<td>LVDT, 10 mV d.c. (S.E. Labs)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>LVDT power supply</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>502A dual beam oscilloscope</td>
<td>M.E.C173</td>
</tr>
<tr>
<td>1</td>
<td>2'x4' retroreflective screen on wood panel (3-M Scotchlite ± 0.127 mm Ø bead size)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>fiber optic cable (Dolan-Jenner BLY-2724) (light source diameter 0.685 mm)</td>
<td></td>
</tr>
</tbody>
</table>
3.1.4 Method

3.1.4.1 Intensity Measurements

3.1.4.1.1 Setup of Equipment

The arrangement of equipment used for intensity measurements is shown schematically and photographically in Figures 3-4 a&b, respectively. Note the on and off axis positioning of the light source in Figure 3-4a. This work was conducted January 1988 in room 215 Essex Hall, University of Windsor.

3.1.4.1.2 Select Images of Contour to Analyze

INT_MAIN was used to measure and record the grey levels for on and off-axis reflex reflection images. The images were recorded for a series of surface contours in the central region of the sheet panel (so as to eliminate 2-D effects), starting with the least discernible image to the extremely distorted. Middle range contour ratios were selected by observing every time the image of the flaw appeared to change detectably from the last noted image. In this manner, a reasonable collection of images for the entire range of contour ratios was obtained. Note that the units for vacuum is in mm Hg for all profiles analyzed. On and off-axis grey level measurements were taken for each contour ratio.
Figure 3-4a Schematic of experimental setup for grey level measurements of reflective panel

Figure 3-4b Photograph of actual setup
The retroreflected image for the 152.4 mm wide central region of the panel was analyzed. In order to select the proper region of the image while focused on the retro. screen when using INT_MAIN, narrow black pinstriping was placed along this outside region of the panel. The retroreflected image of the pinstriping was seen in focus and the boundaries of the region may be selected.

3.1.4.1.3 Integrate and Store Normalized Values of Grey Levels

After the images and normalized grey levels are stored for the various contour ratios using INT_MAIN, each of the curves are integrated twice using INTEGRAL. This required knowing the location where the slope and contour is zero on the surface of the panel. This data was obtained from actual contour measurements using a LVDT.

3.1.4.1.4 Analyze the Data Graphically

The normalized contour, intensity, 1st integration and 2nd integration of the normalized intensity vs. normalized distance were plotted for the contour ratios examined for on and off-axis images. Correlations between the grey levels and the contour shapes were deduced by inspecting these plots.
3.1.4.2 Contour Measurements

The arrangement of equipment used for contour measurements is shown schematically and photographically in Figures 3-5 a&b, respectively. The traverse which moved the LVDT was supported above the panel by two adjustable stands. The traverse support stands were set so the LVDT was tared at both ends of its travel. The LVDT was moved along the surface of the panel using the motor, not by manually turning the shaft of the traverse. Contour measurements were taken every 2 mm for the 152 mm region being analyzed three times for each contour ratio and then averaged. The displacement of the LVDT was measured on an oscilloscope. Appendix II contains LVDT calibration data.

3.1.5 Observations

3.1.5.1 Range of Measurements

A contour ratio of 0.00083 (Wmin=0.0315 mm, Xcontour= 38.1 mm) produced the first optically detectable image of the dent, while contour ratios higher than 0.0023 (Wmin=0.0862 mm) produced distorted retroreflective images because bent light rays from each side of the contour started to cross paths with each other. These images were not analyzed, because the shadowgraph equations presented by Dean [19] state that when bent light rays cross each other, the simple second order relationship between the degree of bending of a light ray and intensity no longer apply. Profiles were analyzed for contour ratios of 0.00083 (10 mm
Figure 3-5a Schematic of experimental setup for contour measurements of reflective panel

Figure 3-5b Photograph of actual setup
Figure 3-6 On-axis retroreflected images of panel analyzed for experiment 1. (W/X=Wmin/Xcontour=contour ratio)
Hg), 0.0011 (20mm Hg), 0.0018 (45mm Hg), 0.002 (54 mm Hg), 0.0022 (60mm Hg) and 0.0023 (64mm Hg). Xmax was 152 mm (6") and 127 mm (5") for on and off-axis imaging respectively. Figure 3-6 shows the on-axis retroreflected images of the panel for the contour ratios examined. The region analyzed for off-axis inspection was not symmetrical about the centre of the contour because the image shifted 25mm (1") to the right. The normalized intensity measurements were noisy for contour ratios 0.00083 and 0.0011 because the changes in intensity were very minor. Striations were seen on the surface of the sheet metal from its forming which are ordinarily not detectable.

3.1.5.2 LVDT Contour Measurements

Orienting the traverse so the LVDT would be nulled at both ends of its travel was difficult to achieve. There was little difficulty moving the LVDT in 2 mm increments.

3.1.6 Results

Figures 3-7a&b to 3-12a&b are plots of normalized intensity (N.I.), normalized 1st and 2nd integration of intensity and normalized contour height (N.C.H) vs. distance for on and off-axis retroreflected concave contour images.

3.1.6.1 Off-axis Results

Figures 3-7b to 3-12b compare the surface contour to the off-axis retroreflected grey levels and its integrals. The plots indicate that the shape of the
normalized off-axis images or its integrals are not proportional to the normalized contour height. This is essentially attributed to a skewing of the grey levels to one side of the centreline of the contour.

3.1.6.2 On-axis Results

The on-axis plots, Figures 3-7a to 3-12a show a correlation between the shape of the normalized contour height and the normalized intensity and the normalized 2nd integral of the normalized intensity. The plots of the 2nd integral of the normalized intensity and the normalized contour heights appear very similar for a contour ratio of 0.00083. The second integral of the normalized intensity curve takes on a shape different from the normalized contour, though not changing in shape very much, for contour ratios higher than 0.00083 (@ 10 mm Hg). The reflected light on the retroscreen (when viewed over the back of the panel) doesn't change significantly either until contour ratios exceed 0.00226 (64 mm Hg). This suggests that the relationship between the retroreflected image and actual shape of a surface contour consists of two components: component 1 is the image seen directly on the retroscreen, which is proportional to the second order of the contour, and component 2, which is the distortion occurring to this image when viewed via reflection from the panel surface. The latter component is proportional to the surface contour.
Intensity and Contour vs. Distance

On Axis, \( W/X = 0.00083 \) @10mm Hg Jan./88

- \( \Box \) measured contour
- \( \Diamond \) 1st integ. of N.I.
- \( + \) norm. intensity
- \( \Delta \) 2nd integ. of N.I.

Normalized Distance on Panel \( (X/X_{\text{max}}) \)

Figure 3-7a
Intensity and Contour vs. Distance

Off Axis, W/X=0.00083 @ 10mm Hg Jan./88

Normalized Distance on Panel (X/Xmax)

- measured contour
- 1st integ. of N.I.
+ norm. intensity
△ 2nd integ. of N.I.

Figure 3-7b
Intensity and Contour vs. Distance

On Axis, W/X=0.00113 @ 20mm Hg. Jan./88

- measured contour
- 1st. integ. of N.I.
+ norm. intensity
Δ 2nd integ. of N.I.

Figure 3-8a
Figure 3-8b

- Measured contour
- 1st integ. of N.L.
- 2nd integ. of N.L.

Normalized Distance on Panel (X/X_{max})
+
Normalized Intensity

Intensity and Contour vs. Distance

Off Axis, W^2/X = 0.00113 \& 20mm Hg. Jan./Feb.
Intensity and Contour vs. Distance

On Axis, W/X = 0.00176 @ 45 mm Hg. Jan./'88

Normalized Distance on Panel (X/X_{max})

- □ measured contour
- □ 1st. integ. of N.I.
- + norm. intensity
- △ 2nd integ. of N.I.

Figure 3-9a
Intensity and Contour vs. Distance

Off Axis, W/X=0.00176 @45mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

- measured contour
- 1st integ. of N.I.
- norm. intensity
- 2nd integ. of N.I.

Figure 3-9b
Intensity and Contour vs. Distance

On Axis, W/\lambda = 0.00174 \@ 54\,\text{nm} Eg. Jan.'88

Normalized Distance on Panel (x/\lambda_{\text{max}}) + norm. intensity + 2nd integ. of N.I.

Figure 3-10a

□ measured contour

△ 1st integ. of N.I.

Normalized Intensity and Contour

36
Intensity and Contour vs. Distance

Off Axis, W/X=0.00217 @60mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

- measured contour
- 1st integ. of N.I.
+ norm. intensity
- 2nd integ. of N.I.

Figure 3-11b
Intensity and Contour vs. Distance

On Axis, W/X=0.00226 @ 64mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

- measured contour
- 1st integ. of N.I.
+ norm. intensity
△ 2nd integ. of N.I.

Figure 3-12a
Intensity and Contour vs. Distance

Off Axis, W/X = 0.00226 @ 64mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

- measured contour
- 1st integ. of N.I.
- 2nd integ. of N.I.
+ norm. intensity

Figure 3-12b
A comparison was made between the normalized contour height (N.C.H.) and the complement of normalized intensity curve. This curve was created by simply subtracting the normalized intensity values from 1, abbreviated as 1-N.I. Also, a comparison was made between the normalized contour height and the curve obtained by averaging the inversion of the normalized intensity, 1-N.I. and the 2nd integral of the normalized intensity, abbreviated 2nd integ. of N.I. The latter comparison appeared to very successful, as indicated in Figures 3-13 to 3-18. From inspection of these plots, one concludes a proportionality exists between the average of the 1-N.I. curve, and the 2nd integ. of N.I. Figures 3-19 to 3-24 plot the percent error between the normalized contour height and the average of the 1-N.I. and 2nd integ. of N.I. curves vs. normalized distance along the contour, defined as:

\[
\text{% error (x)} = \frac{\text{AVG}[2\text{nd integ.}, 1-\text{N.I.}(x)] - [\text{N.C.H.}(x)]}{\text{N.C.H.}(x)} \times 100
\]

The central region in these plots have percent errors in excess of 100% but are ignored because these large errors are attributed to the low value of the contour; in reality the best agreement exists in this region, shown in Figures 3-13 to 3-18.
Intensity and Contour vs. Distance

On Axis, \( W/X = 0.00083 \) @ 10mm Hg Jan./88

- □ measured contour
- × 1-norm. intensity
- ▽ AVG(1-NI, 2nd integ)

Figure 3-13
Intensity and Contour vs. Distance

On Axis, \( W/X = 0.00113 \) @ 20mm Hg, Jan./88

- Square: measured contour
- Triangle: \( \text{AVG}(1-N_1, 2\text{nd integ}) \)
- Cross: 1-norm. intensity

Normalized Distance on Panel \((X/X_{\text{max}})\)

Figure 3-14
Intensity and Contour vs. Distance

Off Axis, \( W/X = 0.00175 \) & 45nm Hg, Jan./88

Normalized Distance on Panel (X/Xmax) × 1-norm. intensity

AVG(1-N,2nd integ) measured contour

Figure 3-15

Normalized Intensity and Contour
Intensity and Contour vs. Distance

On Axis, W/X=0.001974 @ 54mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

□ measured contour
△ AVG(1-N1,2nd integ)
× 1-norm. intensity

Figure 3-16
Intensity and Contour vs. Distance

On Axis, W/X = 0.00217 @ 60mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

□ measured contour
▼ AVG(1-N1,2nd integ)
× 1-norm. intensity

Figure 3-17
Intensity and Contour vs. Distance

On Axis, W/X = 0.00226 @ 64mm Hg. Jan./88

Normalized Distance on Panel (X/X_{max})

- □ measured contour
- × 1-norm. intensity
- ▼ AVG(1-N1,2nd integ)

Figure 3-18
% Error vs. Distance: AVG(1-N1,2ND INT.)

On Axis, W/X = 0.00113 @ 20 mm Hg, Jan./88

Normalized Distance on Panel (X/Xmax)

\[ \square \] % ERROR

Figure 3-20
% Error vs. Distance: AVG(1-NI, 2ND INT.)

On Axis, W/X = 0.00176 @ 45mm Hg. Jan./88

Normalized Distance on Panel (X/Xmax)

□ % ERROR

Figure 3-21
% Error vs. Distance: \text{AVG}(1-N, 2ND INT.)

On Axis, \( W/X = 0.00217 \) @ 60mm Hg. Jan./88

Figure 3-23
% Error vs. Distance: AVG(1-N1, 2ND INT.)

On Axis, \( \frac{W}{X} = 0.00226 \) @ 64mm Hg. Jan./88

Normalized Distance on Panel (\( \frac{X}{X_{\text{max}}} \))

\[ \square \quad \% \text{ ERROR} \]

Figure 3-24
Table 3-1 lists the average and standard deviation of errors occurring between values for the normalized contour height and the complement of the normalized intensity curve, 1-N.I., the 2nd integ. of the N.I. curve, and the average of 1-N.I. and the 2nd integ. of N.I. for all on-axis images.

The error is defined as:

\[ \text{error} = |\text{value on curve} \ n - \text{value on contour}| \]

Note in each case the curve representing the average of the 1-N.I. curve and the 2nd integ. of N.I. curves shows the least error. The average percent error this curve is 17%, with an average precision i.e., the average of the standard deviations of the percent errors for each contour ratio, of 18%.
TABLE 3-1  STATISTICAL ERRORS AND CONTOUR INFORMATION FOR THE CONTOURS ANALYZED

<table>
<thead>
<tr>
<th>Vacuum - mm Hg</th>
<th>10</th>
<th>20</th>
<th>45</th>
<th>54</th>
<th>60</th>
<th>64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour Ratio (Wmin/Xcontour)</td>
<td>0.0008</td>
<td>0.0011</td>
<td>0.0018</td>
<td>0.0022</td>
<td>0.0023</td>
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</table>

CONTOUR DATA

<table>
<thead>
<tr>
<th>Contour Height (Wmax, mm)</th>
<th>0.0202</th>
<th>0.0171</th>
<th>0.0182</th>
<th>0.0171</th>
<th>0.0142</th>
<th>0.0171</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour Depth (Wmin, mm)</td>
<td>-0.0315</td>
<td>-0.0431</td>
<td>-0.0671</td>
<td>-0.0752</td>
<td>-0.0827</td>
<td>-0.0862</td>
</tr>
<tr>
<td>Std. Deviation (for 3 trials) (mm)</td>
<td>0.0009</td>
<td>0.0009</td>
<td>0.0011</td>
<td>0.0010</td>
<td>0.0025</td>
<td>0.0016</td>
</tr>
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</table>

ERROR COMPARISON (From Normalized Plots)

<table>
<thead>
<tr>
<th>2ND INTEGRATION OF NORMALIZED INTENSITY</th>
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</thead>
<tbody>
<tr>
<td>Average Error</td>
</tr>
<tr>
<td>Std. Deviation of Errors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1- NORMALIZED INTENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Error</td>
</tr>
<tr>
<td>Std. Deviation of Errors</td>
</tr>
</tbody>
</table>

AVERAGE OF 2ND INTEGRATION AND 1- NORMALIZED INTENSITY (central regions where percent error ≥ 100 % neglected)

<table>
<thead>
<tr>
<th>Average Error</th>
<th>0.0862</th>
<th>0.1232</th>
<th>0.0924</th>
<th>0.0978</th>
<th>0.0722</th>
<th>0.0954</th>
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<tbody>
<tr>
<td>% Avg. Error</td>
<td>15.83</td>
<td>19.64</td>
<td>15.70</td>
<td>19.02</td>
<td>16.54</td>
<td>16.34</td>
</tr>
<tr>
<td>Std. Deviation of Errors</td>
<td>0.0659</td>
<td>0.0742</td>
<td>0.0713</td>
<td>0.0723</td>
<td>0.0410</td>
<td>0.0732</td>
</tr>
<tr>
<td>% Std. Dev.</td>
<td>17.19</td>
<td>13.87</td>
<td>17.3</td>
<td>21.61</td>
<td>19.14</td>
<td>17.59</td>
</tr>
</tbody>
</table>

56
3.2 Experiment 2 - Dynamic Analysis of a Square Plate

3.2.1 Purpose

The purpose of this experiment is to determine if modal patterns in a vibrating surface may be recognized using primary signature retroreflective imaging.

3.2.2 Experiment Design

3.2.2.1 Subject to Analyze

In order to evaluate the ability of retroreflection for imaging the modal patterns of a vibrating surface, the surface analyzed should be able to maintain a variety of stable and easily recognizable modal shapes. Hazell and Mitchell [16] analyzed the modal shapes of acoustically excited square and rectangular thin plates, clamped along all edges, using holography. Their results showed that a vibrating plate would meet this criteria; therefore, an acoustically excited square plate was chosen for our analysis. The plate assembly used in the experiment is similar to that in ref. 16. A photograph and diagram showing its basic dimensions are shown in Figures 3-25a&b.

3.2.2.2 Measuring Modes of Vibration

The true modal pattern in the vibrating plate was determined by shining spatially filtered coherent HeNe laser light onto the surface of the plate. When the plate is resonating at a natural frequency, laser speckle is observed
Figure 3-25a  Photograph of plate assembly used in experiment 2

Figure 3-25b  Basic dimensions of plate assembly
at the anti-nodes, i.e. the peaks and troughs in the resonating surface; other regions appear as a washed out blur. Although laser speckle does not yield amplitude information as holography does, it also is not as sensitive and serves the purpose of identifying anti-node locations in the experiment.

3.2.2.3 **Capturing Reflex Reflected Modal Images**

Preliminary work revealed that viewing the primary retroreflective image of the vibrating surface under normal continuous light conditions will only show minor disturbances in the surface, even with a point light source. This is attributed to the time averaging of the images in the vibrating surface. Modal shapes become much more pronounced when viewed using a stroboscopic lamp flashing at some whole multiple of the frequency of the vibration. The reflex reflected images can be recorded using a photographic camera under strobe lighting.

3.2.2.4 **Modal Notation**

The notation used by Hazell and Mitchell [16] for describing the modal formations is used here. Mode\((m,n)\) means that there are \(m\) and \(n\) half waves in the mode shape in the \(x\) and \(y\) directions respectively, i.e. the number of nodal lines in the \(x\) and \(y\) directions, where each clamped boundary is considered as half a nodal line, as shown for mode\((1,4)\) in Figure 3-29.
### 3.2.3 Equipment

The following equipment was used in this experiment:

<table>
<thead>
<tr>
<th>QTY</th>
<th>DESCRIPTION</th>
<th>I.D. NO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>strobscopic lamp (General Radio model 1538-A)</td>
<td>95094</td>
</tr>
<tr>
<td>1</td>
<td>photographic camera (Cannon A1 w/ Vivitar 80-200 mm Zoom film: ASA 400 Tri-X Pan B&amp;W film.)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>plate ass'y (plate is 0.3048 m x 0.3048 m x 0.508 mm sheet of yellow brass)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>power amplifier (Brue &amp; Kjaer type 2706)</td>
<td>36959</td>
</tr>
<tr>
<td>1</td>
<td>beat frequency oscillator (Bruel &amp; Kjaer type 1022)</td>
<td>95437</td>
</tr>
<tr>
<td>1</td>
<td>speaker (60 Watt min), 3-magnetic base ass'y</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>fiber optic light source (Cuda model 1-150)</td>
<td>113037</td>
</tr>
<tr>
<td>1</td>
<td>fiber optic cable (Dolan-Jenner BLY-2724)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>8 mW HeNe laser w/ power supply (Spectra Physics)</td>
<td>78580</td>
</tr>
<tr>
<td>1</td>
<td>15u spatial filter (Jodon Engineering)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>front surface flat mirror</td>
<td>95554</td>
</tr>
<tr>
<td>1</td>
<td>3'x4' retroreflective screen mounted in sheet metal (3-M Scotchlite; ±0.127mm ø bead)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>pair construction headphones</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>white powder crack detection kit (Statiflux)</td>
<td>95623</td>
</tr>
</tbody>
</table>
3.2.4 Method

3.2.4.1 Setup Equipment

The experiment was conducted in room 215 Essex Hall, University of Windsor February, 1988. The equipment setup is shown schematically and photographically in Figures 3-26a and 3-26b&c, respectively. The plate was viewed at a high angle to eliminate secondary signature and parallax effects and maximize the width of the retroreflected image.

There was quite a noticeable shift in the retroreflected image of the plate because the camera had to clear the strobe lamp. This shift is shown in Figure 3-27.

3.2.4.2 Obtain Anti-Node Locations Using Laser Speckle

The front surface of the plate was sprayed with a light coat of Statiflux powder. The speaker was positioned in the centre of the back of the plate, at a distance of approximately 10 cm. The spatial filter distributed the laser light in a uniform speckle pattern across the front surface of the plate. The beat frequency oscillator was set at the following settings:

- Output level: 10
- Match Impedance: Att.
- Compressor voltage: 10
- Frequency Dev.: 0
- Comp. Speed: 1000 db/sec.
- Attenuator Output: 12000 mV

NOTE: CONSTRUCTION HEADPHONES WERE WORN FROM THIS POINT ON.
Figure 3-26a Schematic of experimental setup for viewing retroreflection of a vibrating plate

Figure 3-26b Photograph of actual setup; a) retro-reflecting screen b) plate and laser arrangement
strobe lamp

Figure 3-26c  a) Front and b) side views of the camera and strobe lamp

a) Light source above camera (viewer)  b) Light source below camera

Figure 3-27  Shifted retroreflected images of the plate with the light source above and below the viewer.
The power amplifier for the beat frequency oscillator was set so the output was just below signal clipping. The output from beat frequency oscillator was slowly varied from a low to high frequency signal. Frequencies which produced linear, parallel anti-nodes running horizontally on the plate surface were noted. The anti-nodal locations on the plate were sketched because of poor speckle contrast.

3.2.4.3 Record Retroreflective Images Under Stroboscopic and Continuous Lighting

The Statiflux powder was removed from the plate surface. The stroboscope had a sheet of cardboard placed over the front surface of the lamp with an adjustable iris, shown in Figure 3-26c. This aperture was adjusted to yield the best compromise between surface resolution and a uniform light field. The iris was set to 8 mm. A comparison between the retroreflected images of the plate surface at rest using the stroboscopic light source with an iris and the fiber optic light source used in experiment 1 may be seen in Figure 3-28. Both images have similar resolution.

The plate was acoustically vibrated at each of the frequencies noted from the speckle analysis. The retroreflective images of the resonating plate for both stroboscopic and continuous fiber optic light were recorded using a telephoto lens so the picture of the plate covers the entire frame of film. The pictures were taken using black and white ASA 400 film at f/5.6 for one second at opposite phases of the vibration.
Figure 3-28a Static retroreflective image of plate viewed using a fiber optic light source

Figure 3-28b Static retroreflective image of plate viewed using a stroboscopic light source.
In order to successfully photograph modal shapes, the strobe must be synchronized so the movement of the image does not appreciably change throughout the duration of the exposure. The retroreflected image of the plate was photographed above and below the stroboscopic and continuous fiber optic light sources.

3.2.4.4 Correlate Retroreflected Images to Modal Shapes

The retroreflected primary images of the vibrating plate were analyzed noting:

i. Any observable differences between the dynamic and static retroreflection images.

ii. Correlations between anti-node locations indicated by laser speckle and the retroreflected images.

iii. Frequencies or modes where retroreflection works best.

3.2.5 Observations and Results

3.2.5.1 Laser Speckle Modal Pattern

Nodes on the plate were difficult to see using laser speckle, and impossible to record photographically. A better speckle pattern was obtained by coating the surface with "Brasso" brass polish. The Statiflux powder appeared to flake off at certain frequencies, resulting in a new coat of powder having to be applied. Eight frequencies were noted which produced horizontal anti-nodes across the surface of the plate. Sketches of these anti-nodal patterns at the corresponding frequencies are shown in Figure 3-29.
Figure 3-29  Anti-nodal patterns seen in plate using laser speckle
3.2.5.2 Retroreflected Anti-Nodal Patterns

The "retrographs", i.e. photographically recorded retroreflected images, of the vibrating plate seen above and below the continuous point light source used in experiment 1 (time averaged) and the stroboscope, are shown in Figures 3-30 to 3-37. The stroboscopic images yield much better contrast than the fiber optic ones. Visibility for modes (1,3), (1,5), (1,7), (1,9) and (1,11) was good, while modes (1,4), (1,6) and (1,8) was poor. This alternating pattern of good/poor modal visibility suggests that contour visualization using retroreflection is dependent upon the modal shape of the vibrating plate surface. A mode \((\ell, n)\) surface, where \(n\) is an odd number, is symmetrical about its central axis, where even values of \(n\) are not. The contrast of the retrographs did not appear to change with frequency.

3.2.5.3 Comparison Between Static and Dynamic Retroreflection Images

The retrographs of the vibrating plate were compared to retrographs of the static concave-contoured panel of experiment 1 oriented horizontally, shown in Figure 3-38. The images seen on the surface of the resonating plate appear strikingly similar to side by side off-axis static concave contour images, shown in Figure 3-39. This demonstrates that retroreflection is more sensitive to concave contours than convex contours. The dynamic retrographs appear to define a concave contour as starting at the adjacent anti-node peaks of the vibrating surface.
Figure 3-30 Dynamic retroreflective images of a square plate. Freq. = 120 Hz, mode(1,3)
Figure 3-31 Dynamic retroreflective images of a square plate. Freq. = 200 Hz, mode (1,4)
Figure 3-32 Dynamic retroreflective images of a square plate. Freq. = 320 Hz, mode (1,5)
Figure 3-33 Dynamic retroreflective images of a square plate. Freq. = 475 Hz, mode (1,6)
Figure 3-34 Dynamic retroreflective images of a square plate. Freq. = 650 Hz, mode (1,7)
Figure 3-35 Dynamic retroreflective images of a square plate. Freq. = 840 Hz, mode (1,8)
Figure 3-36 Dynamic retroreflective images of a square plate. Freq. = 1000 Hz, mode (1,9)
Figure 3-37 Dynamic retroreflective images of a square plate. Freq. = 1550 Hz, mode (1,11)
a) Retroreflected image of panel with the viewer above the light source

b) Retroreflected image of panel with the viewer below the light source

Figure 3-38 Retroreflected image of panel with horizontal concave contour viewed from above and below the light source.
### 3.2.5.4 Locating Anti-Nodes Using Retroreflection

The continuous light retrographs in Figures 3-30 to 3-37 show only n-1 bright regions for a mode (l,n) surface. The bright regions on the top and bottom of the plate are cut off because the image shifted when viewed off-axis.

In order to verify that the retroreflected intensity patterns represent concave contours, the right half of the plate surface was covered with "Brasso" brass polish and illuminated with the laser light. The plate was then acoustically excited to a frequency causing linear, parallel horizontal anti-nodes to be seen on the surface of the plate using the laser speckle. The reflective left half was illuminated with the strobe light flashing close to some whole multiple of the resonating frequency of the plate. The retroreflective image on the left side of the plate was compared to the anti-nodal locations indicated by the speckle pattern on the right side. This comparison was made from the left side of the light source, not above or below, so the shifting of the retroreflective image was minimized.

The bright regions resembled slowly alternating on-axis static concave contour images centered at the anti-nodes. This verifies that retroreflective imaging of a dynamic surface yields images which magnify the concave contours of its modal shape, when using a continuously emitting fiber optic light source and viewing in a time averaged mode or with the strobe light source.
Figure 3-39 Correlation of modal shape to dynamic retrograph.
[mode(1,5) examined. Note symmetry about central axis]
3.2.5.5 Maintaining A Constant Frequency Signal

The stroboscope and beat frequency oscillator required a lot of adjustment before the retroreflective images on the screen were at their peak intensities and moved slowly enough for a one second exposure to be taken. Appreciable frequency drifting of the beat oscillator was observed after approximately a two to three minute period. It is suspected that the frequency indicated on the scale of the beat oscillator did not accurately match its output.
4. CONCLUSIONS

4.1 Static Analysis - Concave Surface Contour Analysis

4.1.1 Grey Level-Contour Relationship

The results from experiment 1 showed that the intensity in a retroreflected primary image of a concave surface contour is proportional to the average of the complement and second derivative of the contour. Experimental results indicate this relationship consists of two components: component 1 is the image seen directly on the retroscreen, which is proportional to the second derivative of the contour, and component 2, which is the distortion occurring to this image when viewed via reflection from the panel surface. This component related to the contour.

4.1.2 Resolution

This method was able to detect flaws with a contour ratio of 0.00083—or—greater, although the proportionality mentioned in 4.1.1 breaks down for flaw magnitudes greater than 0.00226. Such limitations would not be seen for a convex contour analysis, since the light is dissipated and not concentrated like a concave contour, thus not creating bright regions which cause distortions.
4.1.3 **Accuracy/Precision**

The average accuracy of the relationship stated in 4.1.1 over the entire range of flaw magnitudes examined is 17% error, as defined in 3.1.6, with a precision of 18%.

4.2 **Dynamic Analysis - Modal Imaging of a Vibrating Square Plate**

4.2.1 **Indent Sensitive**

It can be concluded that retroreflection can be used very successfully for determining anti-node locations for vibrating surfaces. Experimental results show that the retroreflective images enhance the concave surface of the plate, whereas the convex surfaces are not seen. The intensity patterns appear immediately side by side; therefore, the period of the contour region occurs between the peaks of adjacent anti-nodes.

4.2.2 **Modal Shape Sensitive**

It may be concluded from the results of experiment 2 that the ability to image a vibrating surface using stroboscopic retroreflection is not limited in frequency range. However, the results indicate that anti-nodal visibility is dependent upon the modal configuration of the vibrating surface. The vibrating plate displayed good visibility for only modes (1,n), where n is an odd number. The reason for this behaviour is not certain.
5. **RECOMMENDATIONS**

5.1 **Experiment 1 - Static Analysis**

In order to improve the quality of experiment 1, the following recommendations are:

i. **Use epoxy to seal the plate to the contour generator.**

   Contour measurements of the plate under no vacuum, after it had been used for a while, indicated that the surface was slightly convex shaped. This is attributed to the silicon sealant creeping when the plate was being sucked in. By sealing the two surfaces together with a film of epoxy, creeping will be greatly reduced. Ensure the two joining surfaces are adequately roughened for a good bond. A fillet of silicon around the perimeter where the panel and the contour generator join could still be used to ensure a good seal.

ii. **Examine convex contours**

   Experiment 1 examined only concave contours. Preliminary examinations of static contours and the results from experiment 2 indicate retroreflection is far more sensitive to concave than convex shaped contours. The modifications to the static contour generator stated in recommendation i would allow the trough to be pressurized with air, creating a convex contour. The exact same method and image analysis software outlined in experiment 1 may be used again.
iii. Examine secondary signature effects

This study did not examine secondary signature contour images. However, this effect can become very important in contour imaging when the viewer and light source are at low angles from the surface. A study which establishes a correlation between the secondary signature image and surface contour is recommended. The results from such a study combined with the work presented in this paper will provide a complete experimental evaluation of the phenomenon of retroreflection.

iv. Develop field equations describing retroreflection phenomenon

The results obtained in this study are purely experimental and should be verified through the development of field equations. By analyzing retroreflection from both theoretical and analytical foundations, the phenomenon will be entirely understood.

5.2 Experiment 2 - Dynamic Analysis

In order to improve experiment 2, the following recommendations are listed:

i. Use a higher intensity strobe light source.

If a higher intensity stroboscopic light source is used, the sensitivity is increased and photographic exposure time reduced. A Xenon-halogen light source, such as the type used in automotive ignition timing lights, is recommended.
ii. Use smaller strobe light source and obtain on-axis results.

The strobe lamp used in experiment 2 is very large and the camera could not obtain an on-axis view of the plate. As a result, the image shifted and relating the location of anti-nodes to the retroreflected image was difficult. The stroboscope should be interfaced with the fiber optic cable used in experiment 1 for on-axis imaging, although this would require a strong light source. If on-axis imaging is impossible, the sides of the plate should be graduated, indicating the distance the off-axis image shifted.

iii. Obtain contour information using holography.

Laser speckle worked well for determining anti-node locations for the plate. If further work is done in correlating the retrographic grey levels of a dynamic surface to the contour deflections, holography could be used to obtain time average amplitude measurements of the surface contour. This information could explain why even numbered modes yield poor visibility.
LIST OF REFERENCES


APPENDIX I

Computer Program FORTRAN Listing
For INT_MAIN and INTEGRAL
INT MAIN: MAINLINE PROGRAM
$INCLUDE: 'FORINTF.H'

THIS PROGRAM IS INTENDED FOR USE WITH A MATROX
PIP-1024 GRAPHICS BOARD. A FRAME IS GRABBED,
AND A REGION IS SELECTED WHERE THE INTENSITY
PROFILE IS PLOTTED. THIS PROFILE IS ONE DIMENSIONAL,
AND THE NORMALIZED INTENSITY, AVERAGED ALONG ONE
AXIS FOR EACH POINT, IS PLOTTED ALONG THE OTHER AXIS.

WRITTEN OCTOBER, NOVEMBER 1987, BY CAM MONTROSE.

*****************************************************************
* LIST OF VARIABLES *
*****************************************************************

AVG(512) - REAL AVERAGE INTENSITY ALONG A
           HORIZ. OR VERTICAL LINE.
BSIZE - SET SIZE OF FRAME BUFFER IN BOARD
         MEMORY.
CHANNO - CHANNEL INPUT ON 1024 BOARD;
         USING VALUE OF 2
C1, C2, C3... - REAL CONSTANTS USED FOR TEMPORARY VALUES
FLAG - FLAG TO LET USER KNOW THAT A
       VERTICAL OR HORIZONTAL AVERAGING
       HAS BEEN TAKEN
I, J, K - LOOP COUNTERS
II, I2, I3... - INTEGER CONSTANTS USED FOR
               TEMPORARY VALUES
INTAVG(512) - NORMALIZED AVERAGE INTENSITY ALONG
              A VERTICAL OR HORIZONTAL STRIP
              = (INT(X,Y) - MIN)/(MAX - MIN)
IMAX - MAXIMUM PIXEL INTENSITY
       ENCOUNTERED ALONG A 512 PIXEL ROW
       OR COLUMN
IMIN - MINIMUM PIXEL INTENSITY ENCOUNTERED
LFB - LEFT BOUNDARY OF REGION ANALYZED ON
      GRABBED FRAME
LWE - LOWER BOUNDARY OF REGION ANALYZED
      ON GRABBED FRAME
NORPOS - NORMALIZED POSITION ALONG AXIS
         PERPENDICULAR TO DIRECTION OF
         AVERAGING - X/WIDTH (VERT.), OR
         Y/WIDTH (HORIZ.)
OFFST - SETTING INITIAL MEMORY LOCATION ON
         BOARD
PART1, PART2 - USED IN CALCULATION OF INTAVG(Y,2)
               IN 2 PARTS
PLOT - A SUBROUTINE USED TO PLOT
       NORMALIZED INTENSITY VS. DISTANCE.
RAVG - TEMPORARY REAL VALUE OF AVG(Y)
REGION - A SUBROUTINE USED TO SQUARE OFF
         REGION TO BE EXAMINED ON VIDEO
         SCREEN.
C RTB - RIGHT BOUNDARY OF REGION ANALYZED ON GRABBED FRAME
C STABLE, USTABLE - VARIABLES FOR CLEARING SCREEN
C STATE - IF STATE=1, 512x512 PIXELS SEEN ON SCREEN
C IF STATE=0, 1024x1024 PIXELS SEEN ON SCREEN
C SUM - INTEGER VALUE TO SUM UP INTENSITIES ALONG HORIZONTAL OR VERTICAL AXIS
C UPB - UPPER BOUNDARY OF REGION ANALYZED ON GRABBED FRAME
C VTYPE - SETS VIDEO STD.; EQUALS 0 FOR AMERICAN
C WIDTH - WIDTH OF AVERAGING REGION; LWB-UPB IF HORIZ., RTB-LFB IF VERT.
C X,Y - INTEGER COORDINATES ON SCREEN (MAX (512,512))

***********************************************************************
* DECLARATION STATEMENTS *
***********************************************************************

IMPLICIT INTEGER*2 (X,Y)
INTEGER*2 OFFST, CHANNO, STATE, STABLE
INTEGER*2 UTABLE, VTYPE, UPB, LWB, RTB
INTEGER*2 LFB, COUNTER, OLDCOUNT
INTEGER*2 BSIZE, QUAD, BUFFER(512)
INTEGER*2 WIDTH, NORPOS, AVG(512)
INTEGER*4 SUM
REAL INTAVG(512,2)
CHARACTER*20 FILENAME, NAME
CHARACTER*2 DUM, WORKBUFFER(256)

***********************************************************************
* DEFINE AND INITIALIZE VIDEO PARAMETERS *
***********************************************************************

OFFST=620
RETV=INIT(OFFST)
CHANNO=2
CALL CHAN(CHANNO)
VTYPE=0
CALL VIDEO(VTYPE)
QUAD=0
CALL QUADM(QUAD)
STABLE=0
UTABLE=7
CALL CLEAR(STABLE, UTABLE)
**DETERMINE WHETHER TO READ FROM FILE OR GRAB PICTURE**

50 WRITE (*,10)
10 FORMAT(//,T5, 'IS PICTURE FROM FILE (F), OR CAMERA (C)? ',/T5, 'ENTER APPROPRIATE LETTER + RETURN - \')
READ (*, '(A1)') DUM
IF ((DUM.EQ. 'F').OR.(DUM.EQ. 'F')) GOTO 20
IF ((DUM.EQ. 'C').OR.(DUM.EQ. 'C')) GOTO 30

WRITE (*,40)
40 FORMAT(//,T5, 'CAN ONLY ENTER C OR F... TRY AGAIN \')
GO TO 50

**READ FROM FILE**

20 CONTINUE

MODE=0
CALL SYNC(MODE)

WRITE (*,60)
60 FORMAT(//,T5, 'ENTER FILENAME - \')
READ (*, '(A20)') FILENAME
BSIZE=1024
II=IFRDSK(BSIZE, QUAD, FILENAME, WORKBUFFER) GOTO 70

**GRAB PICTURE**

30 CONTINUE

MODE=1
CALL SYNC(MODE)
STATE=1
CALL CGRAB(STATE)

WRITE (*,80)
80 FORMAT(//,T15, 'TO GRAB PICTURE: HIT RETURN \')
READ (*, '(A1)') DUM
STATE =0
CALL CGRAB(STATE)
C  ******************************************************************************
C  *  OPTION TO SAVE PICTURE  *
C ******************************************************************************

120 WRITE (*,90)
90 FORMAT (/,'T15,'WISH TO SAVE PICTURE ON DISK ?'
          ,'/,'T15,'ENTER Y (YES) OR N (NO) + RETURN - '
READ (*,'(A1)') DUM

C IF ((DUM.EQ.'y') .OR. (DUM.EQ.'Y')) THEN
   WRITE (*,100)
100 FORMAT ('T15,'ENTER FILENAME - ',
          READ (*,'(A20)') FILENAME
          BSIZE=1024
          I=ITODSK(BSIZE,QUAD,FILENAME,WORKBUFFER)
ELSEIF ((DUM.EQ.'n') .OR. (DUM.EQ.'N')) THEN
   GOTO 70
ELSE
   WRITE (*,110)
110 FORMAT ('T15,'ENTER ONLY Y OR N ... TRY AGAIN'
   GOTO 120

ENDIF

******************************************************************************
C  *  MUST SELECT REGION OF FRAME TO ANALYZE  *
C  *  BY SQUARING OFF REGION  *
C ******************************************************************************

70 CONTINUE
C
CALL REGION(RTB,LFB,UPB,LWB)
LFB=LFB-4
RTB=RTB+4
UPB=UPB-4
LWB=LWB+4

******************************************************************************
C  *  READ INTENSITY OF PIXELS ALONG A ROW OR  *
C  *  COLUMN  *
C  *  DETERMINE THE AVERAGE INTENSITY FOR EACH ROW  *
C  *  OR COLUMN OF PIXELS AND WRITE IT TO A FILE  *
C  *  NORMALIZE THE AVERAGE INTENSITY BASED ON THE  *
C  *  MAXIMUM AND MINIMUM INTENSITY AND WRITE TO  *
C  *  FILE  *
C ******************************************************************************
C
************
C * DECIDE WHETHER TO DO VERTICAL OR HORIZONTAL *
C * EVALUATION *
C
************

170 WRITE (*,130)
130 FORMAT( '0',T5, 'WHICH AXIS WILL INTENSITIES BE AVG.'+
+        ,/T5, '(H)-HORIZ., OR (V)-VERT. + RETURN - ', \
) READ (*, '(A1)') DUM
      IF ((DUM.EQ. 'H').OR.(DUM.EQ. 'h')) GOTO 140
      IF ((DUM.EQ. 'V').OR.(DUM.EQ. 'v')) GOTO 150
C
WRITE (*,160)
160 FORMAT( '//',T5, 'YOU DID NOT HIT H OR V. TRY AGAIN ',/ 
) GOTO 170
C
140 CONTINUE

************
C * AVERAGING ALONG HORIZONTAL AXIS *
C
************

WRITE (*,180) LFB,RTB,UPB,LWB
180 FORMAT ( '0',/T5, 'NOW TO EVALUATE HORIZONTAL AXIS', 
+        ,/T5, 'LEFT BOUNDARY IS ',I3,' PIXELS', 
+        ,/T5, 'RIGHT BOUNDARY IS ',I3,' PIXELS', 
+        ,/T5, 'UPPER BOUNDARY IS ',I3,' PIXELS AND', 
+        ,/T5, 'LOWER BOUNDARY IS ',I3,' PIXELS. '/)
C
************
C * PHASE 1: DETERMINE AVG. INTENSITIES/Y-LINE *
C * AND FIND IMAX AND IMIN *
C
************

IMAX=-10
IMIN= 1000
WIDTH=LWB-UPB
C
DO 190 Y=UPB,LWB,1
  SUM=0
C
  DO 200 X=LFB,RTB
    BUFFER(X)=IPXR(X,Y)
    J=255
    CALL PIXW(X,Y,J)
    SUM=SUM+BUFFER(X)
  C
200 CONTINUE
C
DO 210 X=LFB,RTB
    CALL PIXW(X,Y,BUFFER(X))
210 CONTINUE

94
***DETERMINE AVERAGE INTENSITY, IMAX AND IMIN***

\[ I_1 = RTB - LFB \]
\[ I_2 = \text{SUM} + 0.5 \]
\[ \text{AVG}(Y) = \frac{(\text{SUM} + 0.5)}{(RTB - LFB)} \]

\[ \text{IF} \ (\text{AVG}(Y). \text{GT.} \ IMAX) \ IMAX = \text{AVG}(Y) \]
\[ \text{IF} \ (\text{AVG}(Y). \text{LT.} \ IMIN) \ IMIN = \text{AVG}(Y) \]

190 CONTINUE

\[ \text{PART2} = \text{REAL}(\text{IMAX}) - \text{REAL}(\text{IMIN}) \]

***PRINT RAW VALUES OF AVG(Y) AND NORMALIZED VALUES***

***OPEN UP A FILE AND WRITE AVG(Y) VALUES INTO IT***

\[ \text{WRITE} (*,220) \]
\[ \text{FORMAT} (/,'T5,’ENTER NAME OF FILE TO WRITE’,/,'T5,’NORMALIZED POSITION AND AVG(Y) DATA TO’,\),\]
\[ \text{READ} (*,'(A20,’) FILENAME} \]

\[ \text{OPEN (UNIT=10, FILE=FILENAME, STATUS=’NEW’, ACCESS=’SEQUENTIAL’)} \]
\[ \text{WRITE(10,230) I1} \]
\[ \text{WRITE(10,240) I1} \]

230 \[ \text{FORMAT(’/,’T10,’Y-YMIN)/(YMAX-YMIN’,/,’AVG(Y),//)} \]

240 \[ \text{FORMAT(T15,I3,/) \}} \]

C DO 250 Y=UPB,LWB,1

C DO 260 X=LFB, RTB
\[ \text{BUFFER}(X) = \text{IPXR}(X, Y) \]
\[ J = 255 \]
\[ \text{CALL PIXW}(X, Y, J) \]
C 260 CONTINUE

C INTAVG(Y,1) = REAL(Y-UPB)/REAL(WIDTH)

C RAVG = REAL(AVG(Y))
\[ \text{WRITE (10,270) INTAVG(Y,1), RAVG} \]
\[ \text{FORMAT(T15,F9.4,19X,F9.4)} \]

C DO 280 X=LFB, RTB
\[ \text{CALL PIXW}(X, Y, \text{BUFFER}(X)) \]
C 280 CONTINUE

95
250 CONTINUE
C
CLOSE (UNIT=10)
FLAG=1
C
****************************
* OPEN UP A FILE AND WRITE *
* INTAVG(Y,N) VALUES INTO IT. *
****************************
C
WRITE (*,290)
290 FORMAT (/,'ENTER NAME OF FILE TO WRITE \
,'T5, 'NORMALIZED POSITION AND INTENSITY TO \
,'T5, 'FILENAME \
READ (*, 'A20) ) FILENAME
C
OPEN (UNIT=10, FILE=FILENAME, STATUS= 'NEW',
 ACCESS= 'SEQUENTIAL')
WRITE(10,300)
300 FORMAT(/,'(Y-YMIN)/(YMAX-YMIN)',10X,
 'I(Y)-IMIN)/(IMAX-IMIN)',//)
I1=WIDTH+1
WRITE(10,310) I1
310 FORMAT(T15,I3,/) 
C
****************************
* PHASE 2: DETERMINE INTAVG AND WRITE IT *
* OUT IN A FILE. *
****************************
C
DO 320 Y=UPB,LWB,1
C
DO 330 X=LFB, RTB
 BUFFER(X)=IPIXR(X,Y)
 J=256
 CALL PIXW(X,Y,J)
330 CONTINUE
C
INTAVG(Y,1)=REAL(Y-UPB)/REAL(WIDTH)
PART1=REAL(AVG(Y))-REAL(IMIN)
INTAVG(Y,2)=PART1/PART2
C
WRITE (10,340) INTAVG(Y,1), INTAVG(Y,2)
340 FORMAT(T15,F9.4,19X,F9.4)
C
DO 350 X=LFB, RTB
 CALL PIXW(X,Y,BUFFER(X))
C
350 CONTINUE
C
320 CONTINUE
C
CLOSE (UNIT=10)
FLAG=1
GOTO 540

150 CONTINUE

***--------------------------------------------------------------------------***
* AVERAGING ALONG VERTICAL AXIS *
***--------------------------------------------------------------------------***

WRITE (*,360) LFB,RTB,UPB,LWB

360 FORMAT (/,'NOW TO EVALUATE VERTICAL AXIS',
+      /,'LEFT BOUNDARY IS ',I3,' PIXELS',
+      /,'RIGHT BOUNDARY IS ',I3,' PIXELS',
+      /,'UPPER BOUNDARY IS ',I3,' PIXELS AND',
+      /,'LOWER BOUNDARY IS ',I3,' PIXELS.' /
      )

***--------------------------------------------------------------------------***
* PHASE 1: DETERMINE AVG. INTENSITIES/X-LINE *
* AND FIND IMAX AND IMIN *
***--------------------------------------------------------------------------***

IMAX=-10
IMIN= 1000
WIDTH=RTB-LFB

DO 370 X=LFB,RTB,1
   SUM=0

   DO 380 Y=UPB,LWB,1
      BUFFER(Y)=IPIXR(X,Y)
      J=255
      CALL PIXW(X,Y,J)
      SUM=SUM+BUFFER(Y)

380 CONTINUE

   DO 390 Y=UPB,LWB,1
      CALL PIXW(X,Y,BUFFER(Y))

390 CONTINUE

***--------------------------------------------------------------------------***
* DETERMINE AVERAGE INTENSITY IMAX, AND IMIN *
***--------------------------------------------------------------------------***

AVG(X)=(SUM+0.5)/(LWB-UPB)

IF (AVG(X).GT.IMAX) IMAX=AVG(X)
IF (AVG(X).LT.IMIN) IMIN=AVG(X)

370 CONTINUE

PART2=REAL(IMAX)-REAL(IMIN)

***--------------------------------------------------------------------------***
* PRINT RAW VALUES, OF AVG(X) AND NORMALIZED VALUES *
***--------------------------------------------------------------------------***
C

**************
C * OPEN UP A FILE AND WRITE *
C * AVG(X) VALUES INTO IT *
C

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

WRITE (*,400)

400 FORMAT (/T5,'ENTER NAME OF FILE TO WRITE ',/T5,
+ 'NORMALIZED POSITION AND AVG(X) DATA TO - - ',/)
READ (*,'(A20)') FILENAME

OPEN (UNIT=10,FILE=FILENAME,STATUS='NEW',
+ ACCESS='SEQUENTIAL')
WRITE(10,410)

410 FORMAT(/T10,'(X-XMIN)/(XMAX-XMIN) ',10X,'AVG(X) ',/)
I1=WIDTH+1
WRITE(10,420) I1

420 FORMAT(T15,I3,/

DO 430 X=LFB,RTB,1

430 DO 440 Y=UPB, LWB
  BUFFER(Y)=IPXRX(X,Y)
  J=255
  CALL PIXW(X,Y,J)
  CONTINUE

C

INTAVG(X,1)=REAL(X-LFB)/REAL(WIDTH)

RAVG=REAL(AVG(X))
WRITE (10,450) INTAVG(X,1), RAVG

450 FORMAT(T15,F9.4,19X,F9.4)

DO 460 Y=UPB, LWB
C CALL PIXW(X,Y,BUFFER(Y))

460 CONTINUE

430 CONTINUE

CLOSE (UNIT=10)

FLAG=1

**************
C * OPEN UP A FILE AND WRITE *
C * INTAVG(X,N) VALUES INTO IT *
C

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

WRITE (*,470)

470 FORMAT (/T5,'ENTER NAME OF FILE TO WRITE ',/T5,
+ 'NORMALIZED POSITION AND INTENSITY TO - - ',/)
READ (*,'(A20)') FILENAME

OPEN (UNIT=10,FILE=FILENAME,STATUS='NEW',
+ ACCESS='SEQUENTIAL')
WRITE(10,480)

98
480 FORMAT(//,T10,'(X-XMIN)/(XMAX-XMIN)',10X,'(I(X)-IMIN)/(IMAX-IMIN)',//)
   +I1=WIDTH+1
WRITE(10,490) I1
490 FORMAT(T15,I3,/)  
C     ******************************************************************************
C     * PHASE 2: DETERMINE INTAVG AND WRITE IT OUT IN A FILE. *
C     ******************************************************************************
C     DO 500 X=LFB,RTB,1
C     DO 510 Y=UPB,LWB,1
     BUFFER(Y)=IPIXR(X,Y)
     J=255
     CALL PIXW(X,Y,J)
     CONTINUE
C     INTAVG(X,1)=REAL(X-LFB)/REAL(WIDTH)
     PART1=REAL(AVG(X))-REAL(IMIN)
     INTAVG(X,2)=PART1/PART2
C     WRITE (10,520) INTAVG(X,1), INTAVG(X,2)
520    FORMAT(T15,F9.4,19X,F9.4)
C     DO 530 Y=UPB,LWB,1
     CALL PIXW(X,Y,BUFFER(Y))
C     CONTINUE
C     CONTINUE
C     CLOSE (UNIT=10)
     FLAG=2
C     CONTINUE
C     CALL PLOT(INTAVG,LFB,RTB,UPB,LWB,FLAG)
END
SUBROUTINE REGION: SUBEROGRAM OF INT_MAIN
INCLUDE: 'FORINTF.H'

SUBROUTINE REGION(RTB, LFB, UPB, LWB)

THIS SUBROUTINE (INT_PT2) IS INTENDED FOR USE WITH
A MATROX PIP-1024 GRAPHICS BOARD. THE REGION IN
THE GRABBED IS DETERMINED VIA MOVING BORDERS ALONG
THE RIGHT, LEFT, UPPER AND LOWER BOUNDARIES.

WRITTEN OCTOBER, NOVEMBER 1987, BY CAM MONTROSE.

******************************************************************************
* LIST OF VARIABLES  *
******************************************************************************

BSIZE - SET SIZE OF FRAME BUFFER IN .BOARD MEMORY VALUES
COUNTER - INTEGER COUNTER FOR MISCELLANEOUS PURPOSES
I, J, K - LOOP COUNTERS
I1, I2, I3... - INTEGER CONSTANTS USED FOR TEMPORARY VALUES
LFB - LEFT BOUNDARY OF REGION ANALYZED ON GRABBED FRAME
LWB - LOWER BOUNDARY OF REGION ANALYZED ON GRABBED FRAME
OLDCOUNT - COUNTER-1
RTB - RIGHT BOUNDARY OF REGION ANALYZED ON GRABBED FRAME
UPB - UPPER BOUNDARY OF REGION ANALYZED ON GRABBED FRAME

******************************************************************************
* DECLARATION STATEMENTS  *
******************************************************************************

INTEGER*2 UPB, LWB, RTB, LFB
INTEGER*2 COUNTER, OLDCOUNT
INTEGER*2 BSIZE, QUAD, BUFFER(512), SUM
CHARACTER*20 FILENAME, NAME
CHARACTER*20 DUM, WORKBUFFER(256)

******************************************************************************
* MUST SELECT REGION OF FRAME TO ANALYZE BY SQUARING OFF REGION *
******************************************************************************

CALL SETIND(200)
WRITE (*,10)
10 FORMAT(//,T15,'NOW TO SELECT REGION IN GRABBED FRAME:
                     +,
                     ,/T15)
***************
* LEFT BOUNDARY *
***************

COUNTER=1.

WRITE (*,20)
   FORMAT(/,T5,'LEFT BOUNDARY TO BE DETERMINED - ',/T5,
         + 'HIT RETURN TO MOVE BOUNDARY LINE, ',/T5,
         + 'S + RETURN TO STOP ')

CONTINUE

DO 30 I=1,512,1
   BUFFER(I)=IPIXR(COUNTER, I)
30 CONTINUE

CALL MOVETO(COUNTER, 1)
CALL LINETO(COUNTER, 512)
COUNTER=COUNTER+5
READ(*, '(A1)') DUM
IF ((DUM.EQ. 'S') .OR. (DUM.EQ. 's')) GOTO 60
OLDCOUNT=COUNTER-5

DO 40 I=1,512,1
   CALL PIXW(OLDCOUNT, I, BUFFER(I))
40 CONTINUE

GOTO 50

CONTINUE

LFB=COUNTER
WRITE (*,70) LFB
   FORMAT(/,T5,'LEFT BOUNDARY ',I3,
         + ' PIXELS FROM EDGE OF SCREEN ',/,
         + 'T5,'NOW TO SELECT RIGHT BOUNDARY')

***************
* RIGHT BOUNDARY *
***************

COUNTER=512

WRITE (*,80)
   FORMAT(/,T5,'RIGHT BOUNDARY TO BE DETERMINED - ',/T5,
         + 'HIT RETURN TO MOVE BOUNDARY LINE, ',/T5,
         + 'S + RETURN TO STOP ')

CONTINUE

DO 90 I=1,512,1
   BUFFER(I)=IPIXR(COUNTER, I)
90 CONTINUE
CALL MOVETO(COUNTER, 1)
CALL LINETO(COUNTER, 512)
COUNTER=COUNTER-5
READ(*, '(A1)') DUM
IF ((DUM.EQ. 'S') .OR. (DUM.EQ. 's')) GOTO 100
OLDCOUNT=COUNTER+5

C
DO 110 I=1, 512, 1
   CALL PIXW(OLDCOUNT, I, BUFFER(I))
110 CONTINUE

C
GOTO 120
100 CONTINUE
RTB=COUNTER
II=512-RTB
WRITE (*,130) II
130 FORMAT ('/T5, 'RIGHT BOUNDARY ' , I3,
+ 'PIXELS FROM EDGE OF SCREEN' , '/',
+ 'T5, 'NOW TO SELECT UPPER BOUNDARY')

C

***********************************************************************
C
*       UPPER BOUNDARY       *
C
***********************************************************************

C
COUNTER=1

C
WRITE (*, 140)
140 FORMAT ('/T5, 'UPPER BOUNDARY TO BE DETERMINED -
+ 'HIT RETURN TO MOVE BOUNDARY LINE, ' , '/', T5,
+ 'S + RETURN TO STOP ')

C
180 CONTINUE

C
DO 150 I=1, 512, 1
   BUFFER(I)=IPIXR(I, COUNTER)
150 CONTINUE

C
CALL MOVETO(1, COUNTER)
CALL LINETO(512, COUNTER)
COUNTER=COUNTER+5
READ(*, '(A1)') DUM
IF ((DUM.EQ. 'S') .OR. (DUM.EQ. 's')) GOTO 160
OLDCOUNT=COUNTER-5

C
DO 170 I=1, 512, 1
   CALL PIXW(I, OLDCOUNT, BUFFER(I))
170 CONTINUE

C
GOTO 180
160 CONTINUE
UPB=COUNTER
WRITE (*,190) UPB
190 FORMAT (/,'UPPER BOUNDARY ',I3,
+ 'PIXELS FROM EDGE OF SCREEN' ,/,,
+ 'T5,'NOW TO SELECT LOWER BOUNDRY')

C

***********************************************************************
C *
C LOWER BOUNDARY *
C ***********************************************************************

C COUNTER=480
C
WRITE (*,200)
200 FORMAT (/,'Lower Boundary to be determined. - ',/
+ 'T5, 'Hit return to move boundary line. ',/,'T5,'S + return to stop ')

C

C CONTINUE
C
DO 210 I=1, 512, 1
   BUFFER(I)=IPIXR(I, COUNTER)
210 CONTINUE
C
CALL MOVETO(1, COUNTER)
CALL LINETO(512, COUNTER)
COUNTER=COUNTER-5
READ(*,'(A1)') DUM
IF ((DUM.EQ. 'S') .OR. (DUM.EQ. 's')) GO TO 220
OLDCOUNT=COUNTER+5
C
DO 230 I=1, 512,1
   CALL PIXW(I, OLDCOUNT, BUFFER(I))
230 CONTINUE
C
GOTO 240

C
220 CONTINUE
LWB=COUNTER
II=480-LWB
WRITE (*,250) II
250 FORMAT (/,'Lower Boundary ',I3,
+ 'PIXELS FROM EDGE OF SCREEN',/,
+ 'T5,'NOW TO PROCESS IMAGE IN BOX')
C
RETURN
END
SUBROUTINE PLOT: SUBPROGRAM OF INT_MAIN
SUBROUTINE PLOT(INTAVG,LFB,RTB,UPB,LWB,FLAG)

THIS SUBROUTINE (INT_PT3) WILL DRAW THE REQUIRED
NORMALIZED INTENSITY PLOTS ON THE SCREEN, AND SAVE
THE FINAL PICTURE.

WRITTEN OCTOBER, NOVEMBER 1987, BY CAM MONTRÔSE.

************************************************************************************
* LIST OF VARIABLES *
************************************************************************************

BSIZE. - SET SIZE OF FRAME BUFFER IN BOARD
         MEMORY PURPOSES
FLAG. - FLAG TO LET USER KNOW THAT A
        VERTICAL OR HORIZONTAL AVERAGING
        HAS BEEN TAKEN
I, J, K - LOOP COUNTERS
INTAVG(512) - NORMALIZED AVERAGE INTENSITY ALONG
              A VERTICAL OR HORIZONTAL STRIP
              = (INT(X,Y)-IMIN)/(IMAX-IMIN)
LFB - LEFT BOUNDARY OF REGION ANALYZED
      ON GRABBED FRAME
LWB - LOWER BOUNDARY OF REGION ANALYZED
      ON GRABBED FRAME
RTB - RIGHT BOUNDARY OF REGION ANALYZED
      ON GRABBED FRAME
SCALE - SCALE OF LETTERING - USUALLY 1-3
STR - STRING VARIABLE - CONTAINS TITLE
       STATEMENT
UPB - UPPER BOUNDARY OF REGION ANALYZED
      ON GRABBED FRAME
WIDTH - WIDTH OF AVERAGING REGION;
         LWB-UPB IF HORIZ., RTB-LFB IF VERT.
X,Y - INTEGER COORDINATES ON SCREEN (MAX
      (512,512))

************************************************************************************
* DECLARATION STATEMENTS *
************************************************************************************

IMPLICIT INTEGER*2 (X,Y)
EXTERNAL IPIXR
EXTERNAL RECIF
INTEGER*2 OFFST, CHANNO, STATE, STABLE
INTEGER*2 UTABLE, VTYPE, UPE, LWB, RTB
INTEGER*2 LFB, COUNTER, OLDCOUNT
INTEGER*2 BSIZE, QUAD, BUFFER(512), SUM
INTEGER*2 WIDTH, NORPOS, SCALE
REAL*4 INTAVG(512,2)
CHARACTER*20 FILENAME, NAME
CHARACTER*2 DUM, WORKBUFFER(256)
CHARACTER*50 STR
C
C
C
C
C
C
IF (FLAG.EQ.1) THEN
  GOTO 10
ELSEIF (FLAG.EQ.2) THEN
  GOTO 20
END IF

C
C
C
C
C
C
CALL SETIND(200)
CALL RECTF(1,UPB,300,LWB)

C
C
C
C
C
C
CALL SETIND(100)
DO 30 I=1,11,1
   I1=50+200*(I-1)/10
   CALL MOVETO(I1,UPB)
   CALL LINFO(I1,LWB)
30  CONTINUE

C
C
C
C
C
C
CALL SETIND(200)
CALL RECTF(50,430,500,450)
CALL SETIND(10)
CALL MOVETO(100,446)
SCALE=1
STR='(Y-YMIN)/(YMAX-YMIN) VS. (Y-YMIN)/(YMAX-YMIN)
CALL TEXT('STR',SCALE)
CALL MOVETO(30,UPB+20)
SCALE=2
STR='0'
CALL TEXT('STR',SCALE)
CALL MOVETO(275,UPB+20)
STR='1'
CALL TEXT('STR',SCALE)
CALL SETIND(10)
SCALE=1
DO 40 Y=UPB,LWB
   CALL MOVETO(50,Y)
   I1=50+200*INTAVG(Y,2)
   CALL MOVETO(I1,Y)
   I2=I1-4
   CALL LINETO(I2,Y)
40 CONTINUE
GOTO 50

CALL SETIND(200)
CALL RECTF(LFB,150,RTB,450)

CALL RECTF(50,430,500,450)
CALL SETIND(10)
CALL MOVETO(100,446)
SCALE=1
STR='(IX-IMIN)/(IMAX-IMIN) VS. (X-XMIN)/(XMAX-XMIN)
CALL TEXT (STR,SCALE)
CALL MOVETO (LFB,420)
SCALE=2
STR='0
CALL TEXT (STR,SCALE)
CALL MOVETO (LFB,180)
STR='1
CALL TEXT (STR,SCALE)
CALL SETIND(100)
SCALE=1
DO 60 I=1, 11, 1
   I1=400-200*(I-1)/10
   CALL MOVETO(LFB, I1)
   CALL LINETO(RTB, I1)
CONTINUE

CALL SETIND(10)
DO 70 X=LFB, RTB
   I1=400-200*INTAVG(X, 2)
   CALL MOVETO(X, I1)
   I2=I1+4
   CALL LINETO(X, I2)
CONTINUE

CONTINUE

*** OPTION TO SAVE FINAL PICTURE ***

WRITE (*, 80)
FORMAT(/, T5, 'WANT TO SAVE FINAL PICTURE ?', /, + 'Y (YES) OR N (NO) + RETURN', \)
READ (*, '(A1)') DUM

IF ((DUM.EQ. 'Y') OR (DUM.EQ. 'Y')) THEN
   WRITE (*, 90)
   FORMAT(/, T5, 'ENTER FILENAME - ', \)
   READ (*, '(A20)') FILENAME
   BSIZE=1024
   I1=ITODSK(BSIZE, QUAD, FILENAME, WORKBUFFER)
ELSEIF ((DUM.EQ. 'N') OR (DUM.EQ. 'N')) THEN
   GOTO 100
ELSE
   WRITE (*, 110)
   FORMAT(/, T5, 'ENTER ONLY Y OR N ... TRY AGAIN', /)
   GOTO 120
ENDIF

CONTINUE
RETURN
END
INTEGRAL: MAINLINE PROGRAM
$INCLUDE: 'FORINTF.H'

THIS PROGRAM READS FROM DISK AND PLOTS A SET OF DATA
(PIC.DAT) AND THEN PERFORMS INTEGRATION ON THIS SET OF
DATA. THIS NEW SET OF DATA (INTEGRAL.DAT) IS AGAIN
RE-NORMALIZED AND PLOTTED ON TOP OF THE ORIGINAL
CURVE. THE PROCESS MAY BE REPEATED.

WRITTEN JANUARY, 1988 BY CAM MONTROSE.

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

* LIST OF VARIABLES *
******************************************************************************

A - LOCATION ENTERED FOR NORMALIZED WIDTH
   FOR WHICH THE REAL VALUE OF THE
   INTEGRAL IS KNOWN
B - REAL VALUE OF INTEGRAL AT A
DIFFERENCE - ABSOLUTE REAL VALUE OF DATA(I,1)-
   CLOSEST
DATA(I,J) - DATA MATRIX DATA (I,1) NORMALIZED
   LOCATION, DATA (I,2) NORMALIZED
   INTENSITY; REAL VALUED, READ IN.
FILENAME - CHARACTER VARIABLE FOR NAME OF FILE
GAP - ALLOWABLE DIFFERENCE IN LOCATION OF
   INTEGRAL VALUE CONDITION TO CLOSEST
   DATA POINT.
HIGH - REAL UPPER LIMIT USED TO FIND ZERO-
I - INTEGER VALUED LOOP COUNTER
(POSSIBLY SPECIFIED ON SITE)
JCLOSEST - INTEGER VALUED VARIABLE THAT HOLDS
   DATA(I,1)
INTEGRAL(I,J) - DATA MATRIX DATA (I,1) NORMALIZED
   LOCATION, DATA (I,2) NORMALIZED
   INTENSITY
J,K,L - INTEGER VALUED LOOP COUNTERS
   (POSSIBLY SPECIFIED ON SITE)
LOW - REAL LOWER LIMIT USED TO FIND ZERO
MAX - REAL MAXIMUM VALUE ENCOUNTERED, USED IN
   NORMALIZATION.
MIN - REAL MINIMUM VALUE ENCOUNTERED, USED IN
   NORMALIZATION.
NORMINT - DIMENSIONED ARRAY CONTAINING NORMALIZED
   INTEGRAL VALUES.
NPTS - NUMBER OF POINTS; INTEGER VALUED.
OLDZERO - OLD-REAL VALUE OF ZERO.
PLOTGRID - SUBROUTINE THAT MAKES THE GRID,
   BACKGROUND ETC.. FOR PLOTTING A LINE
   ONTO.
PLOTVAL - SUBROUTINE THAT PLOTS VALUES ONTO GRID.
   (NPTS,DATA)
or (NPTS,B)
SUM - REAL VARIABLE USED FOR INTEGRATION
TEXT - CHARACTER VARIABLE THAT READS TITLES IN
   DATA FILES. (CHARACTER VARIABLE)
WIDTH - INTEGRATION USES SUM OF SMALL RECTANGLES METHOD EACH RECTANGLE HAS A HEIGHT DATA(I,2) AND WIDTH 1/NPTS
ZERO - REAL VALUE USED AS ZERO LINE IN INTEGRATION ROUTINE. FOUND BY CONDITION OF INTEGRAL

******************************************************************************
** DECLARATION STATEMENTS **
******************************************************************************
DIMENSION DATA(512,2),
        CHARACTER*20, TEXT*25, DUM*5
        CHARACTER WORKBUFFER (256)
        INTEGER*2 FLAG, OFFST, CHANNO, STATE, STABLE
        INTEGER*2 UTABLE, VTYPE, BSIZE, QUAD, RETX
        REAL*4 LOW, MAX, MIN, INTEGRAL(512,2)
        REAL*4 NORMINT(512,2)

******************************************************************************
** OPEN UP AND READ IN DATA FROM FILE **
******************************************************************************
WRITE (*,10)
10 FORMAT (/,'ENTER FILENAME TO READ DATA FROM - ',/)
READ (*,'(A20)') FILENAME
OPEN (UNIT=10, FILE=FILENAME, STATUS='OLD', +
      ACCESS='SEQUENTIAL')

******************************************************************************
** FORMAT TO READ NPTS FROM FILE **
******************************************************************************
READ (10,20) NPTS
20 FORMAT (///,'T15,I3,'/

******************************************************************************
** FORMAT TO PRINT NPTS TO SCREEN **
******************************************************************************
WRITE(*,30) NPTS
30 FORMAT(/,'NO. OF DATA POINTS = ',I5,/)

DO 40 I=1,NPTS,1

******************************************************************************
** FORMAT TO READ DATA FROM FILE **
******************************************************************************
READ(10,50) DATA(I,1), DATA(I,2)
50 FORMAT(T15,F9.4,19X,F9.4)
**FORMAT TO PRINT DATA TO SCREEN**

```c
WRITE(*,60) I,DATA(I,1),I,DATA(I,5)
```

```c
40 CONTINUE
CLOSE(UNIT=10)
```

```c
60 WRITE (*,70)
70 FORMAT(/,T5,'PLOT DATA THAT HAS BEEN READ IN ?'
+ ,'/,T5,'ENTER Y (YES)- OR N (NO) - '
) READ (*,'(A2)') DUM
```

```c
IF ((DUM.EQ.'Y').OR.(DUM.EQ.'y')) THEN
```

```c
FLAG=0.0
CALL PLOTGRID
CALL PLOTVAR(NPTS, DATA, FLAG)
```

```c
ELSEIF ((DUM.EQ.'N').OR.(DUM.EQ.'n')) THEN
GOTO 130;
```

```c
ELSE
WRITE (*,140)
140 FORMAT(/,T5,'WRONG KEY, ... TRY AGAIN !')
GOTO 60
ENDIF
```

```c
130 CONTINUE
```

```c
460 CONTINUE
```

**START THE INTEGRATION PROCESS**

```c
WRITE(*,160)
160 FORMAT(/,T5,'FILL IN THE FOLLOWING....'
+ ,'/,T5,'AT X/W (NORMALIZED WIDTH) = A'
+ ,'/,T5,'THE INTEGRAL OF THE FUNCTION = B'
+ ,'/,T5,'INPUT A - '
) READ (*,* ) A
```

113
WRITE(*,170)
170 FORMAT(/,T5,`INPUT B - `)
READ(*,*) B

WRITE (*,180) A,B
180 FORMAT(/,T5,`AT X/W (A) = `,F8.3,`, INTEGRAL (B) =` + ,F8.3,/)  

******************************************************************************
* DETEMINE DATA(I,1) THAT MOST CLOSELY * 
* CORRESPOND TO A; i.e., FIND ICLOSEST * 
******************************************************************************

GAP=10000.
ICLOSEST=10000

DO 190 I=1,NPTS,1
  DIFFERENCE=ABS(DATA(I,1)-A)
  IF (DIFFERENCE.LT.GAP) THEN
    ICLOSEST=I
    GAP=DIFFERENCE
  ELSE
    CONTINUE
  ENDIF
190 WRITE(*,200) ICLOSEST, A, GAP
200 FORMAT(`+`,T5,`DATA POINT `,I4,`, IS CLOSEST TO `,F8.3, 
      ` THE DIFFERENCE IS `,E12.4,)

******************************************************************************
* FIND THE ZERO POINT THAT WILL SATISFY * 
* CONDITION OF INTEGRAL. * 
* START MINI-INTEGRATIONS UP TO DATA * 
* (ICLOSEST,1) WITH ZERO LINE INITIALLY * 
* AT (HIGH+LOW)/2 (INITIALLY, 0=LOW AND * 
* 1 T HIGH). IF INTEGRAL AT DATA (ICLOSEST, * 
* 1) IS +`VE, THEN ZEROLINE = (ZERO+HIGH)/ * 
* 2; LOW= OLDZERO. IF INTEGRAL AT DATA * 
* (ICLOSEST,1) IS -`VE, THEN ZERO = (LOW+ * 
* ZERO)/2, HIGH=OLDZERO. REPEAT UNTIL * 
* SUFFICIENT CONVERGENCE IS ACHIEVED. * 
******************************************************************************

HIGH=1000.
LOW=0.0
WIDTH=1./REAL(NPTS)

SUM=0.0

230 ZERO=(HIGH+LOW)/2.0
230 WRITE (*,210) HIGH,LOW,ZERO,WIDTH,SUM
210 FORMAT(/,`HIGH=`,F7.4,` LOW=`,F7.4,` ZERO=`,+F7.4,` WIDTH=`,F7.4,` SUM=`,F7.4,` +RETURN`,/) 
READ(*,`(A1)`) DUM

SUM=0.0
DO 220 I=1,ICLOSEST,1
   SUM=SUM+(DATA(I,2)-ZERO)*WIDTH
   CONTINUE
C
IF (SUM.GT.0.001) THEN
   LOW=ZERO
   GOTO 230
ELSEIF (SUM.LT.-0.001) THEN
   HIGH=ZERO
   GOTO 230
ELSE
   ENDIF
C
WRITE (*,240) HIGH, LOW, ZERO, SUM
C240 FORMAT(+'+', 'HIGH = ',F7.4, ' LOW = ',F7.4, ' ZERO = ',
    +' +', F7.4, ' SUM= ',F7.4,
C
C
C
C
C
C
C
C
SUM=0.0
DO 250 I=1,NPTS,1
   INTEGRAL(I,1)=DATA(I,1)
   SUM=SUM+(DATA(I,2)-ZERO)*WIDTH
   INTEGRAL(I,2)=SUM
   CONTINUE
C
C
C
C
C
C
MAX=-10000.
MIN= 10000
C
DO 260 I=1,NPTS,1
   IF (INTEGRAL(I,2).GT.MAX) THEN
      MAX=INTEGRAL(I,2)
   ELSEIF (INTEGRAL(I,2).LT.MIN) THEN
      MIN=INTEGRAL(I,2)
   ELSE
      ENDIF
C
C
C
C
C
C
DO 270 I=1,NPTS,1
   NORMINT(I,2)=(INTEGRAL(I,2)-MIN)/(MAX-MIN)
270 CONTINUE
C
C
C
C
C
C
C
FLAG=1
CALL PLOTTVAL(NPTS, NORMINT, FLAG)
C ********************************************************************
C * OPTION TO SAVE INTEGRAL IN A DATA FILE *
C ********************************************************************

350 WRITE (*,280)
280 FORMAT(/,T5,`SAVE-UNNORMALIZED INTEG. DATA ON FILE ?`,+,
     /,T5,`Y- (YES), N- (NO), + RETURN - `,\)
     READ (*,`'(A2)`) DUM

C IF ((DUM.EQ.`Y`).OR.(DUM.EQ.`y`)) THEN
   WRITE (*,290)
290 FORMAT(/,T5,`ENTER NAME OF FILE TO WRITE `,/,T5,`UNNORMALIZED VALUES TO `,\)
     READ (*,`'(A20)`) FILENAME

C OPEN (UNIT=10,FILE=FILENAME,ACCESS=`SEQUENTIAL`,+,
     STATUS=`NEW`)

C WRITE(10,300) NPTS
300 FORMAT(/,T10,`(X-XMIN)/(XMAX-XMIN)`),10X,+
     `(I(X)-IMIN)/(IMAX-IMIN)`),//,T15,I3,/,)

C DO 310 I=1,NPTS,1
   WRITE(10,320) INTEGRAL(I,1),INTEGRAL(I,2)
320 FORMAT(T15,F9.4,19X,F9.4)
  CONTINUE
C CLOSE (UNIT=10)
C ELSEIF ((DUM.EQ.`N`).OR.(DUM.EQ.`n`)) THEN
   GOTO 330
C ELSE
   WRITE (*,340)
340 FORMAT(/,T5,`WRONG KEY, ... TRY AGAIN ! `)
   GOTO 350
ENDIF
330 CONTINUE

C ********************************************************************
C * OPTION TO SAVE NORMINT IN A DATA FILE *
C ********************************************************************

430 WRITE (*,360)
360 FORMAT(/,T5,`SAVE NORMALIZED INTEG. DATA ON FILE ?`,+,
     /,T5,`Y- (YES), N- (NO), + RETURN - `,\)
     READ (*,`'(A2)`) DUM

C IF ((DUM.EQ.`Y`).OR.(DUM.EQ.`y`)) THEN
   WRITE (*,370)
370 FORMAT(/,T5,`ENTER NAME OF FILE TO WRITE `,/,T5,`NORMALIZED INTEGRATED VALUES TO `,\)
     READ (*,`'(A20)`) FILENAME

C
OPEN (UNIT=10, FILE=FILENAME, ACCESS='SEQUENTIAL',
    STATUS='NEW')

WRITE (10, 380) NPTS
FORMAT (//, T10, '(X-XMIN)/(XMAX-XMIN)', 10X,
    '(I(X)-IMIN)/(IMAX-IMIN)', ///, T15, I3, //)

DO 390 I=1, NPTS, 1
   WRITE (10, 400) DATA(I, 1), NORMINT(I, 2)
   FORMAT (T15, F9.4, 19X, F9.4)
390   CONTINUE

CLOSE (UNIT=10)

ELSEIF ((DUM.EQ.'N').OR.(DUM.EQ.'n')) THEN
   GOTO 410

ELSE
   WRITE (*, 420)
   FORMAT (/, T5, 'WRONG KEY...TRY AGAIN!')
   GOTO 430
ENDIF

CONTINUE

***********************************************************************
* ASK IF PROCESS IS TO BE REPEATED FOR ANOTHER ORDER?
***********************************************************************

WRITE (*, 440)
FORMAT (/, T5, 'DO YOU WISH TO PERFORM ANOTHER INTEGR.?', +
    'ENTER Y (YES), N (NO) + RETURN ', \)
READ (*, '(A5)') DUM

IF ((DUM.EQ.'Y').OR.(DUM.EQ.'y')) THEN
   DO 450 I=1, NPTS
      DATA(I, 2) = INTEGRAL(I, 2)
   CONTINUE
   GOTO 460
ENDIF

IF ((DUM.EQ.'N').OR.(DUM.EQ.'n')) GOTO 470

WRITE (*, 480)
FORMAT (/, T5, 'WRONG KEY: HIT ONLY Y OR N..TRY AGAIN!' +
    'ENTER ', //)
   GOTO 490

CONTINUE

END

117
SUBROUTINE PLOTVAL: SUBPROGRAM OF INTEGRAL
SUBROUTINE PLOTVAL(NPTS, DATA, FLAG)

THIS SUBROUTINE (PLOTVAL) WILL PLOT THE NPTS
NORMALIZED VALUES PROVIDED BY DATA ONTO THE
GRID PROVIDED BY PLOTGRID.

WRITTEN OCTOBER, NOVEMBER 1987, BY CAM MONTROSE.

***********************************************************
* LIST OF VARIABLES *
***********************************************************

DATA(512,2) - INPUT DATA: DATA(I,1) = X VALUE
               DATA(I,2) = Y VALUE
FLAG - IF FLAG=0: SETIND(10) RAW DATA
       IF FLAG=1: SETIND(50) FITTED CURVE
I - LOOP COUNTERS
J - DATA(I,1) CLOSEST TO PIXEL I
K - DATA(I,2) TRANSFORMED INTO COORD.'S
    ON PIXEL REGION.
L - COUNTER TRANSFORMED INTO PIXEL
    COORD.'S
M - CREATES WIDTH OF LINE FOR PLOTTED
    DATA.
NPTS - NUMBER OF POINTS PROVIDED BY DATA
STR - STRING VARIABLE - CONTAINS TITLE
       STATEMENT

***********************************************************
* DECLARATION STATEMENTS *
***********************************************************

INTEGER*2 OFFST, CHANNO, STATE, STABLE, UTABLE
INTEGER*2 SCALE, BSIZE, QUAD, FLAG
DIMENSION DATA(512,2)
CHARACTER*20, DUM*2, WORKBUFFER(256)*2

***********************************************************
* PLOT INTENSITY PROFILE ON SCREEN *
***********************************************************

SCALE=1
IF (FLAG.EQ.0) CALL SETIND(10)
IF (FLAG.EQ.1) CALL SETIND(50)

***********************************************************
* DRAW LINE *
***********************************************************

WRITE(*,10) NPTS, FLAG
10 FORMAT(/,T5,'RUNNING SUBROUTINE PLOTVAL',/ +     ,T5,'NO. OF POINTS = ',I5,/ +     ,T5,'FLAG = ',I1,/)

119
DO 20 I=1,NPTS,1
WRITE (*,30) I, DATA(I,1), I, DATA(I,2)
FORMAT ('+', T5, 'DATA(', I3, ',')= ', F9.4, T5, 'DATA(', I3, ',', I2)= ', F9.4)
CONTINUE

IF (NPTS.GE.350) THEN

******************************************************************************
* IF THE NO. OF DATA POINTS IS GREATER THAN PLOT POINTS *
******************************************************************************

** PLOT THE FIRST POINT **
******************************************************************************

K=INT (REAL ((1.-DATA(1,2))*350.0+0.5)+50)
L=70
CALL MOVETO(L,K)
M=K+4
CALL LINETO(L,M)

******************************************************************************
* PLOT EVERY (NPTS-1)*(I-1)/349 IN BETWEEN *
******************************************************************************

DO 40 I=2,350,1
   J=INT (REAL ((NPTS-1)*(I-1)/349))
   K=INT (REAL ((1.-DATA(J,2))*350.0+0.5)+50)
   L=70+I
   CALL MOVETO(L,K)
   M=K+4
   CALL LINETO(L,M)
40 CONTINUE

ELSE

******************************************************************************
* IF THE NO. OF DATA POINTS IS LESS THAN PLOT POINTS *
******************************************************************************

** PLOT THE FIRST POINT **
******************************************************************************

K=INT (REAL ((1.-DATA(1,2))*350.0+0.5)+50)
L=70
CALL MOVETO(L,K)
M=K+4
CALL LINETO(L,M)
DO 50 I=2,NPTS-1,1
   L=INT((350.0/(NPTS-1))*(I-1))+70
   K=INT(REAL((I-DATA(I,2))*350.0+0.5)+50)
   CALL MOVETO(L,K)
   M=K+4
   CALL LINETO(L,M)
50 CONTINUE

ENDIF

******************************************************************************
* OPTION TO SAVE FINAL PICTURE *
******************************************************************************

100 WRITE (*,60)
60 FORMAT (/,'T5, 'WANT TO SAVE FINAL PICTURE ? ',/,'T5, 'Y (YES) OR N (NO) + RETURN ',"
READ (*,'(A1)') DUM

IF ((DUM.EQ. 'Y').OR.(DUM.EQ. 'Y')) THEN
   WRITE (*,70)
70 FORMAT(/,'T5, ENTER FILENAME - ',"
   READ (*,'(A20)') FILENAME
   BSIZE=1024
   I1=ITODSK(BSIZE,QUAD,FILENAME,WORKBUFFER)
ELSEIF ((DUM.EQ. 'N').OR.(DUM.EQ. 'n')) THEN
   GOTO 80
ELSE
   WRITE (*,90)
90 FORMAT(/,'T5, ENTER ONLY Y OR N ... TRY AGAIN ')
   GOTO 100
ENDIF
80 CONTINUE
RETURN -
END
SUBROUTINE PLOTGRID: SUBPROGRAM OF INTEGRAL
`INCLUDE 'FORINTF.H'

SUBROUTINE PLOTGRID

THIS SUBROUTINE (PLOTGRID, FOR) WILL DRAW THE
BACKGROUND, GRID, AND AXIS FOR NORMALIZED DATA
TO BE PLOTTED ONTO.

WRITTEN NOVEMBER, NOVEMBER 1987, BY CAM MONTROSE.

******************************************************************************
* LIST OF VARIABLES *
******************************************************************************

BSIZE - SET SIZE OF FRAME BUFFER IN BOARD MEMORY PURPOSES
I, J, K - LOOP COUNTERS
SCALE - SCALE OF LETTERIN - USUALLY 1-3
STR - STRING VARIABLE - CONTAINS TITLE STATEMENT
WIDTH - WIDTH OF AVERAGING REGION;
        LWB-UPB IF HORIZ., RTB-LFB IF VERT.

******************************************************************************
* DECLARATION STATEMENTS *
******************************************************************************

INTEGER*2 OFFST, CHANNO, STATE, STABLE
INTEGER*2 UTABLE, VTYPE
INTEGER*2 BSIZE, QUAD, BUFFER(512), SUM
INTEGER*2 WIDTH, NORPOS, SCALE
CHARACTER*20 FILENAME, NAME
CHARACTER*2 DUM, WORKBUFFER(256)
CHARACTER*50 STR

******************************************************************************
* INITIALIZE VIDEO SYSTEM *
******************************************************************************

OFFST=620
RETV=INIT(OFFST)
CHANNO=2
CALL CHAN(CHANNO)
MODE=0
CALL SYNC(MODE)
VTYPE=0
CALL VIDEO(VTYPE)
QUAD=0
CALL QUADM(QUAD)
STABLE=0
UTABLE=7
CALL CLEAR(STABLE, UTABLE)
* PLOT INTENSITY PROFILE ON SCREEN *

** ****
* DRAW RECT. *
** ****
SCALE=1
CALL SETIND(260)
CALL RECTF(0,0,510,510)

** ****
* DRAW TITLE BLOCK *
** ****
CALL SETIND (10)
STR='(IX-IMIN)/(IMAX-IMIN) VS. (X-XMIN)/(XMAX-XMIN)
CALL MOVETO (65,440)
CALL TEXT (STR, SCALE)

** ****
* DRAW X GRID (VERT.) *
** ****
CALL SETIND(150)
DO 10 I=1,11,1
  I1=70+350*(I-1)/10
  CALL MOVETO(I1,50)
  CALL LINETO(I1,400)
10 CONTINUE

** ****
* DRAW X GRID LABELS *
** ****
CALL SETIND(10)
SCALE=2

STR = '0.0
CALL MOVETO(50,420)
CALL TEXT(STR,SCALE)

STR = '0.2
CALL MOVETO(120,425)
CALL TEXT(STR,SCALE)

STR = '0.4
CALL MOVETO(190,425)
CALL TEXT(STR,SCALE)

STR = '0.6
CALL MOVETO(260,425)
CALL TEXT(STR,SCALE)
```
STR = '0.8
CALL MOVETO(330,425)
CALL TEXT(STR,SCALE)

STR = '1.0
CALL MOVETO(400,425)
CALL TEXT(STR,SCALE)

*****************************************************************************
*     DRAW Y GRID (HORIZ.)     *
*****************************************************************************

CALL SETIND(150)
SCALE=1

DO 20 I=1,11,1
   I1=50+350*(I-1)/10
   CALL MOVETO(70,I1)
   CALL LINETO(420,I1)
20 CONTINUE

*****************************************************************************
*     DRAW Y GRID LABELS     *
*****************************************************************************

CALL SETIND(10)
SCALE=2

STR = '0.0
CALL MOVETO(20,400)
CALL TEXT(STR,SCALE)

STR = '0.2
CALL MOVETO(20,330)
CALL TEXT(STR,SCALE)

STR = '0.4
CALL MOVETO(20,260)
CALL TEXT(STR,SCALE)

STR = '0.6
CALL MOVETO(20,190)
CALL TEXT(STR,SCALE)

STR = '0.8
CALL MOVETO(20,120)
CALL TEXT(STR,SCALE)

STR = '1.0
CALL MOVETO(20,50)
CALL TEXT(STR,SCALE)

RETURN
END
```
APPENDIX II

Calibration Data For LVDT
<table>
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<tr>
<th>INPUT (cm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4 (inches)</th>
<th>5</th>
<th>6</th>
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</tbody>
</table>

**TRIAL** | **SLOPE - M (inches/mV)** | **INTERCEPT - B (inches)** |
---|---|---|
1 | 2.70807E-04 | 1.9264E-05 |
2 | 2.86491E-04 | -3.18423E-05 |
3 | 2.84421E-04 | -1.56836E-05 |
4 | 2.89368E-04 | -3.11044E-05 |
5 | 2.87017E-04 | -1.57889E-05 |
6 | .000268 | -1.07361E-05 |

\[ \text{M} = 2.84352E-04 \]
\[ \text{B} = -1.43186E-05 \]
\[ \text{STD. DEV. (PRECISION)} = 3.28387E-05 \]
\[ \text{REPEATABILITY} = 4.56939E-05 \]

**CALIBRATION FACTOR** \( m^* \) = \( 2.8435 \times 10^{-5} \) inches \( \text{mV}^{-1} \) \( \times 25.4 \text{mm} = 7.223 \times 10^{-5} \) mm \( \text{mV}^{-1} \)
<table>
<thead>
<tr>
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<th>OUTPUT - TRIAL NO. 5 [mV/cm]</th>
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<table>
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<th>INTERCEPT - B (inches)</th>
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</table>

M = 6.83247E-04
B = 1.88146E-05
STD. DEV. (PRECISION) = 5.5059E-05
REPEATABILITY = 1.80451E-05

**CALIBRATION FACTOR** $m = 6.8325 \times 10^{-4} \text{ in.} / \text{mV} \times 25.4 \text{ mm} = 17.355 \times 10^{-3} \text{ mm} / \text{mV}.$
VITA AUCTORIS

1962  Born in Oakville, Ontario


1985  Received the degree of Bachelor of Applied Science in Mechanical Engineering from the University of Windsor, Windsor, Ontario, Canada.

1988  Currently, a candidate for the degree of Master of Applied Science in Mechanical Engineering at the University of Windsor.