



QAS/62

The Fringe-Imaging Skin Friction Technique PC Application User's Manual

Gregory G. Zilliac

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

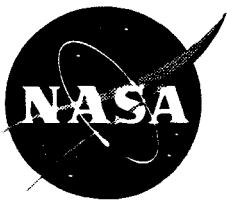
- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:
NASA Access Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320



The Fringe-Imaging Skin Friction Technique PC Application User's Manual

Gregory G. Zilliac

Ames Research Center, Moffett Field, California

**National Aeronautics and
Space Administration**

**Ames Research Center
Moffett Field, California 94035-1000**

Acknowledgments

I would like to thank Bruce Rapaport and Dave Driver for their substantial contributions to this work.

NOTICE

Use of trade names or names of manufacturers in this document does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

THE FRINGE-IMAGING SKIN FRICTION TECHNIQUE PC APPLICATION USER'S MANUAL

Gregory G. Zilliac

Ames Research Center

SUMMARY

A personal computer application (CXWIN4G) has been written which greatly simplifies the task of extracting skin friction measurements from interferograms of oil flows on the surface of wind tunnel models. Images are first calibrated, using a novel approach to one-camera photogrammetry, to obtain accurate spatial information on surfaces with curvature. As part of the image calibration process, an auxiliary file containing the wind tunnel model geometry is used in conjunction with a two-dimensional direct linear transformation to relate the image plane to the physical (model) coordinates. The application then applies a nonlinear regression model to accurately determine the fringe spacing from interferometric intensity records as required by the Fringe Imaging Skin Friction (FISF) technique. The skin friction is found through application of a simple expression that makes use of lubrication theory to relate fringe spacing to skin friction.

INTRODUCTION

CXWIN4GG is a PC application useful for determining the skin friction at points on a surface. It is specifically designed to process the interferograms that are imaged as part of the FISF technique. If one has a grayscale TIF image of an FISF interferogram (image should have fiducial marks), knows the wavelength of the light that created the interferogram, the viscosity of the oil that was used and the duration that the oil was exposed to the flow, the skin friction magnitude and direction can be found with minimal effort. CXWIN4G has the following features:

- High accuracy nonlinear regression-based fringe spacing identification.
- Single-camera photogrammetry for measurement location determination.
- Automatic Delaunay triangulation of datapoints.
- Graphical display of skin friction results.

The FISF technique is described in great detail in references 1–4. In short, a drop (or line) of silicon oil of known viscosity is placed on the prepared surface of a wind tunnel model near the desired measurement location. The air flow is turned on and the oil spreads. After approximately two to ten minutes, the oil forms a wedge (in cross section) with a nearly linear profile. The flow is turned off. At this point, an extended quasi-monochromatic light source (wavelength of λ), pointed toward the

surface, will create an interference pattern caused by the reflection of light from the top surface of the oil interfering with light reflected from the prepared test surface at the oil-surface interface (see fig. 1). This pattern can be imaged using a monochrome digital camera. The distance Δs between the destructive interference bands (dark lines) of the interferogram is proportional to the thickness of the oil and, in turn, proportional to the skin friction (by lubrication theory; ref. 2) as follows:

$$c_f = \frac{\tau_w}{q_\infty} = \frac{2n_o\mu_o\Delta s}{q_\infty\lambda t} \cos(\theta_r) \quad (1)$$

for zero pressure and shear stress gradients where C_f is the skin friction coefficient, τ_w is the wall shear stress, q_∞ is the freestream dynamic pressure, n_o is the oil index of refraction, μ_o is the oil absolute viscosity, t is the duration of oil exposure to the air flow and θ_r is the light refraction angle through the air-oil interface. In practice, the product $\frac{\mu_o}{q_\infty t}$ in equation (1) is often replaced by $1/\int_0^{t_{run}} \frac{q_\infty}{\mu_o} dt$ when wind tunnel startup and shutdown time (off condition) are a significant portion of the total run time or the temperature variation is significant.

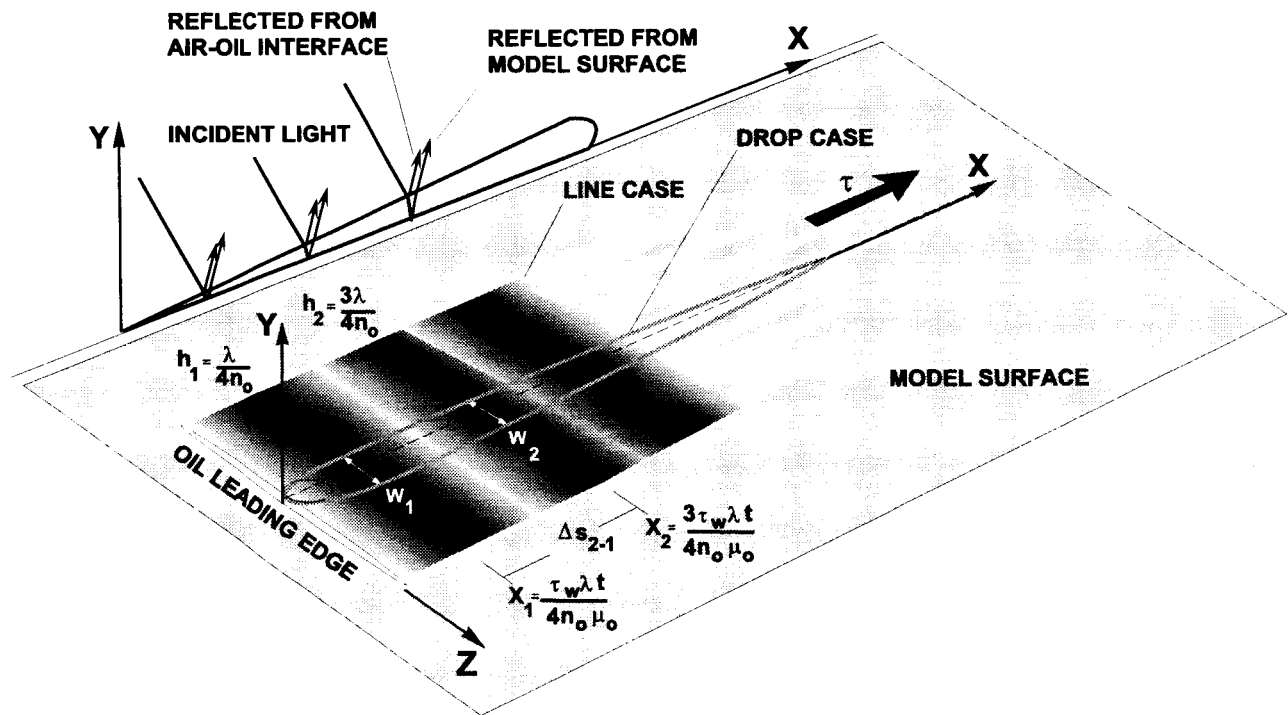


Figure 1. Schematic of an FISF oil flow.

This inclusion of the $\cos(\theta_r)$ term in equation (1) arises from the fact that fringe spacing is dependent on the location of the light source relative to the surface of the model or more precisely, the path that the light takes through the oil. If the light source is positioned so that the light rays strike the model normal or near-normal to the surface, then this term is equal or close to 1.0. In some wind tunnel tests, light is bounced off of the walls of the wind tunnel in order to achieve complete and even illumination of the surface. Under these conditions, the $\cos(\theta_r)$ term can have an appreciable impact on the skin friction measurement. The light refraction angle through the air-oil interface is related to the light incidence angle on the oil by $\theta_r = \text{asin}(\sin\theta_i/n_o)$.

The light incidence angle θ_i is automatically determined by the PC application through the use of photogrammetry. In short, this is achieved by first finding the position vector of the camera relative to an FISF measurement point location, followed by the determination of the surface normal and application of the law of reflection (see fig. 2).

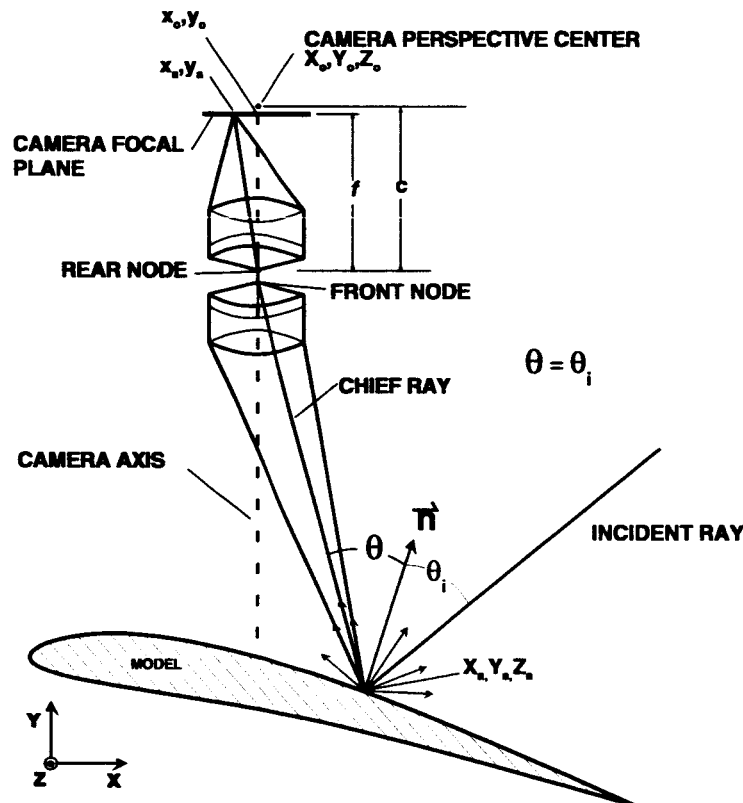


Figure 2. Optical path and photogrammetry.

At the heart of the PC application is a nine parameter model which is fit to the fringe-intensity distribution using a nonlinear regression algorithm. The advantage of this approach to fringe spacing determination is that the model is derived from the physics of interferometry. It makes allowances for such effects as surface curvature, noise, small optical imperfections and nonuniform lighting. In addition, the whole intensity record is used by the regression to identify the fringe spacing (as opposed to schemes which simply fit the peaks of the intensity distribution). The model is given by:

$$I = B_1 + B_2s + B_3s^2 + (E_1 + E_2s + E_3s^2)\cos(P_1 + P_2s + P_3s^2) \quad (2)$$

where I is the intensity, s is the distance along the centerline of the oil streak (in pixels), B , E and P are the regression coefficients (see refs. 1 and 5).

The skin friction coefficient magnitude is determined by using a fringe spacing found from the regression followed by a conversion of the pixel-based fringe spacing to physical coordinates (via photogrammetry) and application of equation (1). The direction of the skin friction vector is found by determining the orientation of the oil pathline relative to a fixed coordinate system.

The accuracy of FISF skin friction measurements is dependent on many factors (see ref. 1) including camera resolution and temperature. Using CXWIN4G with properly resolved interferometric images, one can expect to achieve skin friction measurements that have uncertainties in the ballpark of $\pm 5\%$ and skin friction vector direction uncertainties of $\pm 1^\circ$. Even lower uncertainty can be had under some circumstances (for instance, if the temperature of the oil is known to better than 0.5°F).

THE CXWIN4G PC APPLICATION

Minimum Computer Requirements

- IBM or compatible 486 or better with 32 Mb Ram
- VGA graphics card
- Windows 95 or NT 4
- CD-ROM drive
- 5 Mb of free disk space

Installation Procedure

Included on the CXWIN4G CD Rom is version 4 of the application, the Visual Microsoft C++ project file (source code, make file,...etc.) and some sample FISF images and CXWIN4G data bases. To install CXWIN4G:

1. Copy the **expskin** folder to the hard disk. For ease of use, it is recommended that the **expskin** folder reside in the top level of the hard disk folder structure. (Note: The **imglib.dll** file must reside in the same folder as **CXWIN4G.EXE**.)
2. Verify that your video adapter is set to 256 colors (using the control panel). A good monitor resolution to use is 800×600 pixels. Less than this resolution may result in a portion of the screen not being visible.

Note for Windows NT users. If CXWIN4G is going to be used to process very large image files (4k×4k pixels or bigger), increasing the size of the virtual memory may speed up the application.

Reading an Image

The application is fairly straightforward to use. Assuming that one is starting with a grayscale TIF file of an FISF interferogram and desires to obtain contour maps or vector plots of the surface skin friction distribution, the following steps should be followed:

I. Read in the image.

1. Left-double click on the CXWIN4G icon.
2. Left-click on the **Read File** button in the main CXWIN4G window.
3. Enter the data (such as oil viscosity, run time,...etc.) in the “Data” popup dialog box which appears after the **Read File** button is hit. Note: Enter data only in the non-gray fields. One can choose what data to enter by changing the “Freestream Properties ” radiobutton.
4. Enter the “Appended char.” (maximum of eight characters, case sensitive) in the appropriate field.
5. Click on **OK**.
6. Left-double click on the appropriate TIF image file in the “Read an Image From a File” popup dialog box. The screen should be like that shown in figure 3.

The “Data” dialog box (shown in fig. 4) is the control window for the FISF part of the application. It has controls for the line width used in extraction of the fringe intensity distribution, default I/O directories, measurement point location, and the quantities required by equation (1). Four freestream property data input options are available. One can enter q_∞ and T ; or P_{total} , M_∞ and T ; or $\int_0^{t_{run}} q_\infty dt$ and T or $\int_0^{t_{run}} (q_\infty/\mu) dt$. The choice is made by clicking on the desired radiobutton in the “Freestream Properties” section of the “Data” dialog box. Only data for the user’s choice need be entered. Units are cs for ν , nm for the light source wavelength, sec for t , in. H₂O for q_∞ , °F for T , psi for P_{total} , in. H₂O sec for $\int_0^{t_{run}} q_\infty dt$ and in. H₂O sec/(slugs/ft sec) for $\int_0^{t_{run}} (q_\infty/\mu) dt$. The choice of units were based on personal preference and over the development of this application these units have become so embedded that a change would be very difficult at this time.

If desired, the user can bring up the “Data” dialog box again by depressing the center mouse button to switch to high-resolution mode, followed by clicking the “Data” button. The buttons along the top of the screen are active only when the image is in high-resolution mode (high-resolution mode is one screen pixel for every image pixel).

The oil viscosity termed “Nom Kin Visc” is the oil kinematic viscosity at 77°F (25°C) in centistokes. If this value is not known, it can be determined using equations shown in the miscellaneous section of this guide.

When the **Read File** button is depressed, the same “Data” dialog box appears on the screen. When this dialog box is closed, CXWIN4G creates a log file (filename **XXXXXXXXX.log**; see Appendix A

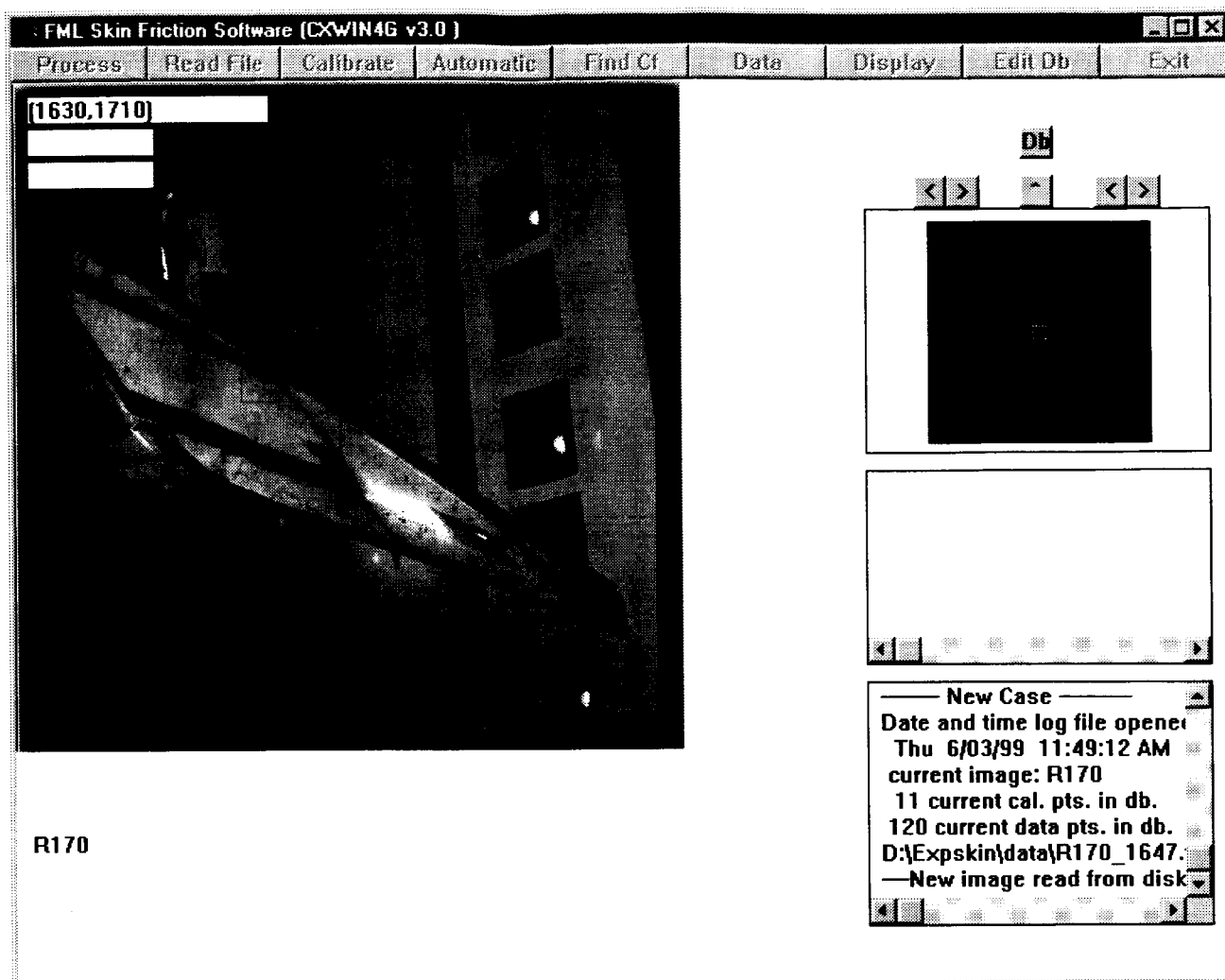


Figure 3. Main CXWIN4G window with image shown in low-resolution mode.

for a Input/Output file summary) in the **disk:\expskin\data** directory where **XXXXXXXXXX** are the case sensitive "Appended Char." previously entered in the "Data" dialog box. (Note that the default CD-ROM drive and the hard-disk i/o directories can be changed within the "Data" dialog box.) The same "Data" dialog box can be opened by clicking on the **Data** button, and the data fields modified, at any point while CXWIN4G is in the high-resolution display mode.

It is good practice to enter some if not all of the same characters to the "Appended char." prompt (in the Data popup dialog box) as are used in the image file name. The "appended char." are used to construct intermediate and output file names and also as labels to distinguish data in the database file and hence, following this procedure will help avoid confusion. Different "appended char." should be used for each new image in a dataset.

The data initially shown in the "Data" popup dialog originates from the **disk:\expskin\default.dat** ASCII disk file. This file can be edited and modified by the user prior to running CXWIN4G.

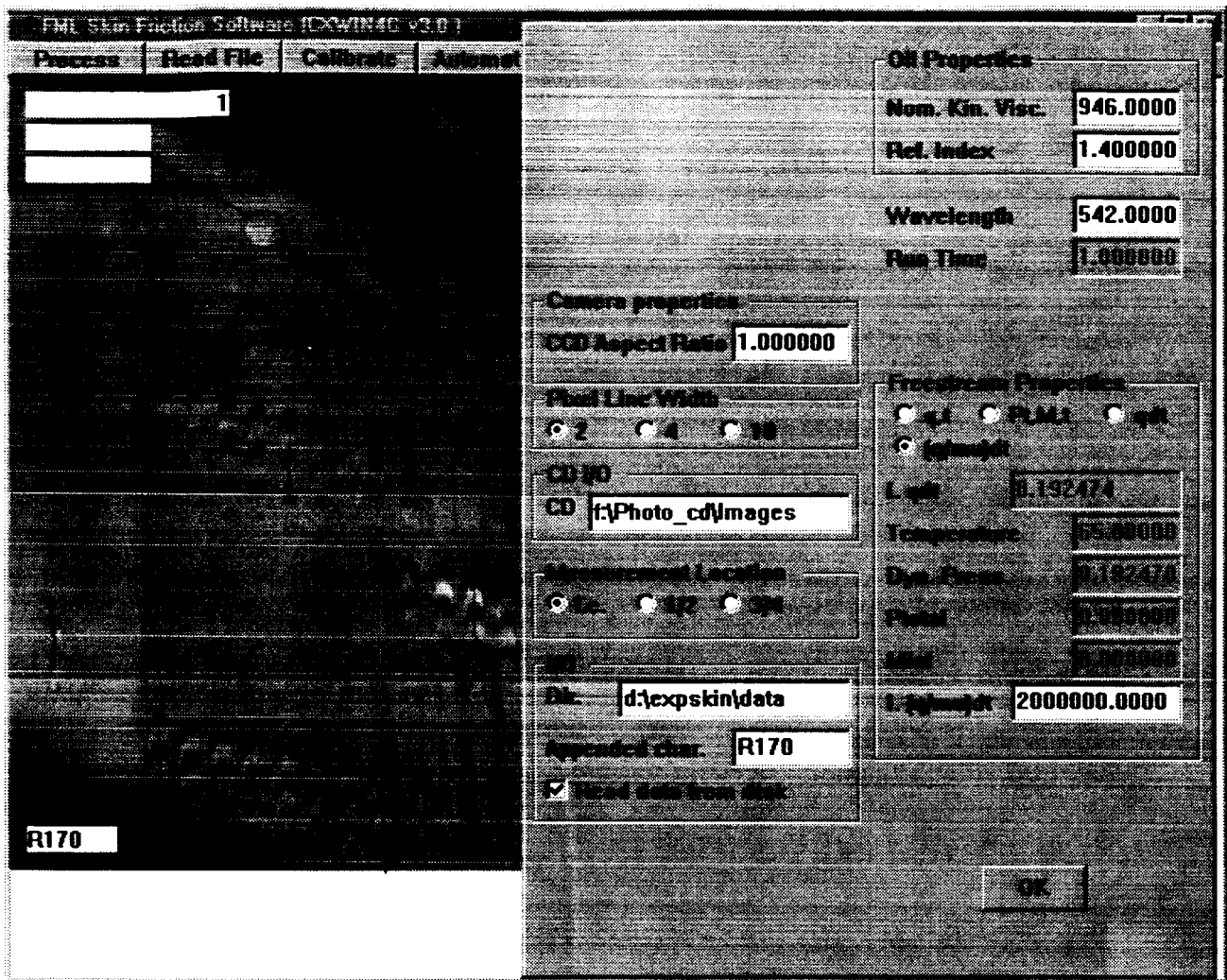


Figure 4. Main window with the “Data” dialog box open.

In the “Data” popup dialog box, there is a “Read data from disk” checkbox (see fig. 4). If this box is checked, the numerical data need not be entered in the fields of this dialog box. CXWIN4G will look for an ASCII file containing this data in the **disk:\expskin\data** folder. The name of this user-created file should be **texpXXXXXXXX.dat** where **XXXXXXXX** are the user specified appended characters. The **texpXXXXXXXX.dat** file contains one line with space-separated data in the following order: oil nominal kinematic viscosity in cs, oil index of refraction, light source wavelength in nm, the run time in sec, the integral over the run time of the dynamic pressure in in. H₂O sec, the temperature of the oil in °F, the dynamic pressure in in. H₂O, the total pressure in psi, the freestream Mach number, the light reflection angle in degs and the integral over the run time of the dynamic pressure divided by the oil absolute viscosity in in. H₂O sec/(slugs/ft sec). One can enter 0 for quantities in this file that are not required by CXWIN4G (indicated by the grayed out fields in the “Data” popup dialog box) for the particular “Freestream properties” option chosen.

Also of importance in the “Data” popup dialog box is an entry for “CCD Aspect Ratio.” This camera property is the ratio of the physical distance between pixels top to bottom divided by the distance between pixels from right to left ($\Delta y/\Delta x$).

At this point, the image file should now be present on the screen. This image is displayed at the highest resolution that will fit on a 486×512 pixel window. A cross-cursor centered red box will also be present on the screen. This box shows the area of the image that will be displayed when the application is put into its high-resolution mode. Note that at this point, if the image is bigger than 486×512 pixels, the only option is to change resolutions since the cursor is confined to within the bounds of the image. To change to the high-resolution display, position the cross over the point of interest and click the center button (or use the **Esc** key if the mouse being used has only two buttons). At high resolution, the image is displayed such that one screen pixel is one pixel in the TIF file. Note: All operations are performed in the high-resolution mode. The low-resolution mode is used only for repositioning within the image.

Image Spatial Calibration

In the literature, image calibration (or camera calibration) refers to the process of mapping pixels in the image to physical coordinates on a surface. The mapping (i.e., photogrammetry) approach used in CXWIN4G is further described in Appendix B.

II. Calibrate the image.

1. Switch the image to high-resolution mode (mouse middle button or **Esc**).
2. With the image displayed at high resolution, click on the **Calibrate** button at the top of the main window. A popup dialog box will appear (see fig. 5) wherein the coordinate plane, which most closely parallels that of the image, (either xy , xz or yz) should be selected. Also, in this dialog box, enter the distance of the camera (in inches) and the value of the length scale used to scale the auxiliary data (discussed in a later section).
3. Position the cross cursor over the first calibration point (a point in the image where the X, Y, Z location is known) and left-click. A popup dialog box will appear and the X, Y and Z coordinates (in inches) of the calibration point should be entered. Fine adjustment of the calibration point pixel locations can be done using the arrow keys after closing the popup dialog box (prior to next left-click). Note: It may be necessary to switch back and forth between the high- and low-resolution mode. A green cross will be displayed on the image at the locations of calibration points entered. Repeat step 3 for all of the calibration points.
4. Right-click on the image when all of the calibration points have been entered. A "Calibration Complete" message should appear. The calibration data will then be automatically stored in **default.bas** (the CXWIN4G data base file).

The camera distance entered above is the coordinate of the camera's perspective center in the X, Y, Z coordinate system (enter the X_o, Y_o or Z_o perspective center coordinate normal to the plane that is most closely aligned with the model surface). For most cameras, the camera perspective center is located approximately at the center point of the film plane (see fig. 2). This distance is used solely in the determination of θ_r and high precision is usually not of paramount importance. In situations where a pinhole approximation of the camera is not a good approximation, (i.e., multi-element lens, short object distance...etc.) it may be more appropriate to enter the coordinate of the front or rear lens node to obtain a better measure of θ_r .

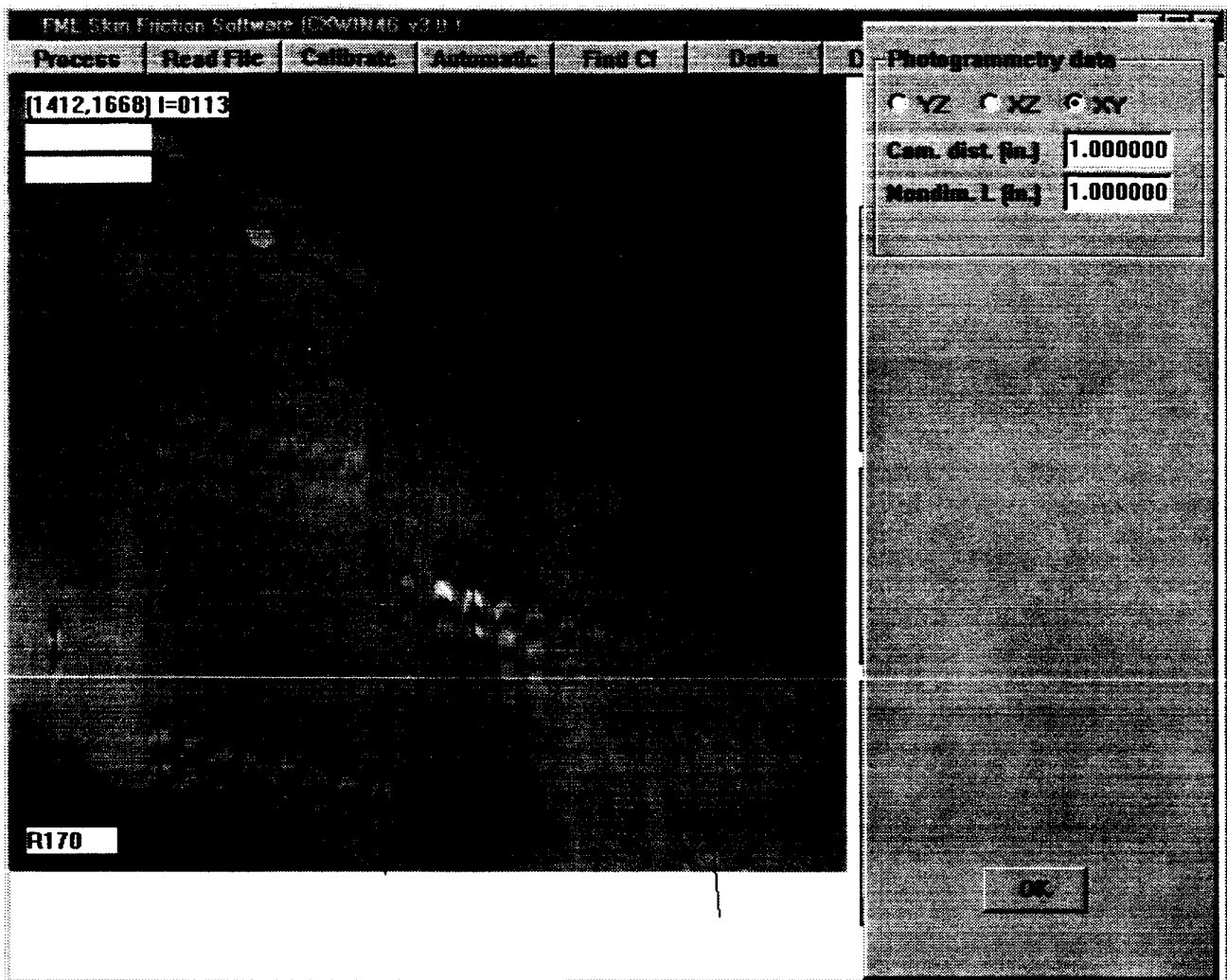


Figure 5. Main window with the “Photogrammetry data” dialog box open.

The purpose of the “xy, xz or yz” selection made in the “Photogrammetry Data” dialog box is to instruct CXWIN4G as to how to use the data in the **surfpts.dat** file in the scattered data interpolation process. For instance, if “xy” is chosen, the X, Y, Z data in **surfpts.dat** will be interpolated to determine Z .

The calibration process is the way that the application spatially relates pixels (x, y) in the image plane to the physical surface (X, Y, Z) . One-camera photogrammetry is the basis of this process. A minimum of four points are required but in practice, 10 to 15 should be used to obtain a reasonable level of accuracy. Pre-drawn targets located at known X, Y, Z 's prior to imaging are commonly used for this purpose. (The X, Y, Z coordinate system must be a right-handed system.) It is important that care be taken during the calibration process because the calibration affects the fringe spacing and light angle determination in addition to the measurement point location. Calibration will be discussed in greater detail in a later section of this guide.

Find the Fringe Intensity Distribution

The fringe intensity distribution is found by drawing a line (straight or curved) normal to the fringe fronts starting upstream of the oil flow and extending downstream of the second fringe (the dark portion of the pattern is commonly referred to as a fringe).

III. Extract the fringe intensity data from the interferogram.

1. While the image is in high resolution mode, place the cursor upstream of the first fringe and left-click.
2. Move the cursor to a point downstream of the second fringe and left-click.
3. Add additional points as required to define a curved line along which the intensity is desired (works well for up to 6 points in total).
4. Right-click and the intensity distribution (along the line drawn on the image) should appear in the upper-right child window (see fig. 6).

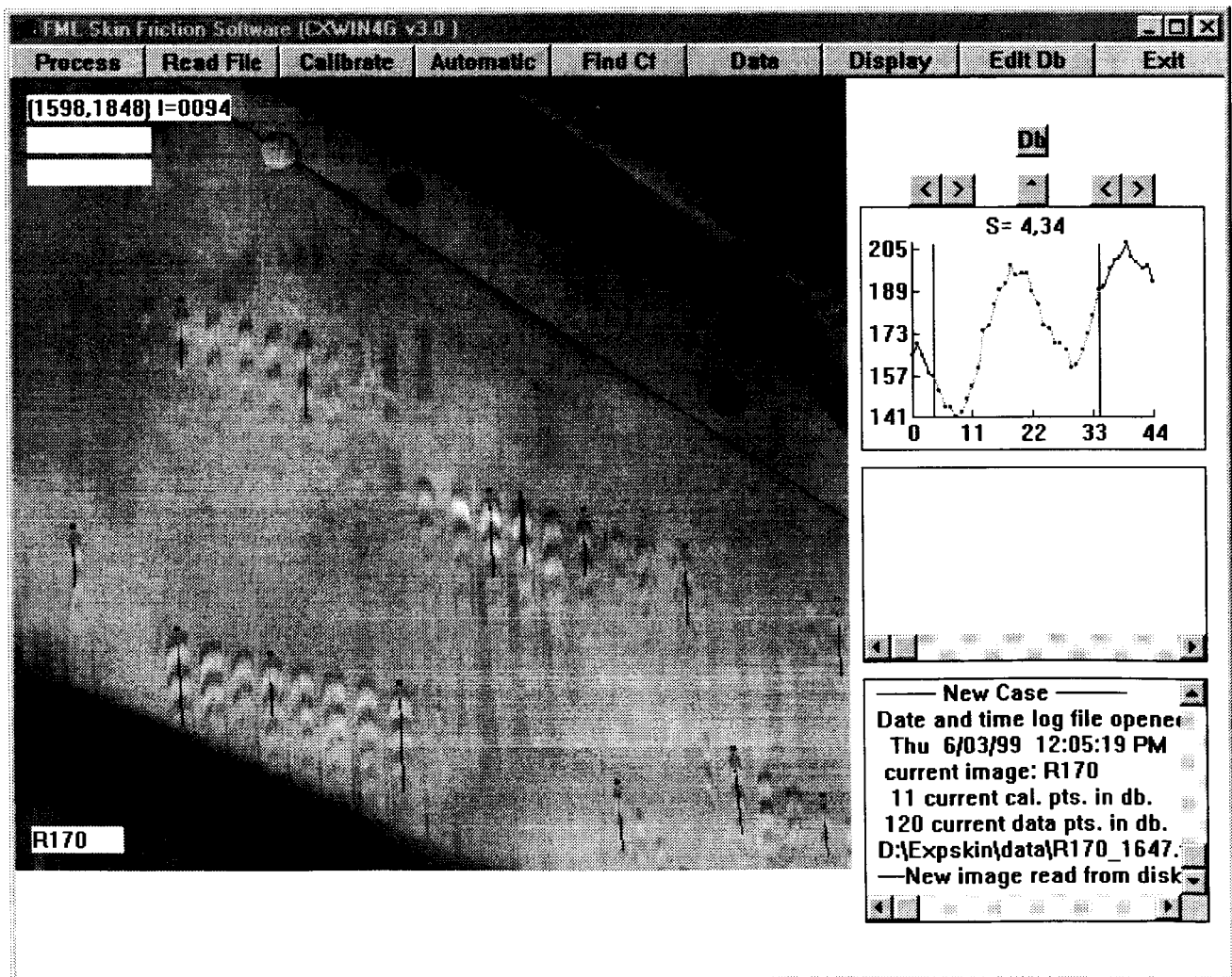


Figure 6. Fringe pattern intensity distribution (upper-right child window).

The line drawn on the image in the above steps should always be drawn in the direction of the oil flow as this is the way CXWIN4G determines the skin-friction vector direction. On well resolved fringe patterns and with some practice, this can usually be done to within a degree of the actual direction. Fine adjustment of the point locations used to define the line drawn on the image can be made using the arrow keys following mouse left-clicks. This line should begin upstream of the oil; otherwise, the algorithm used to locate the leading edge of the oil may fail. Typically, only the segment of the intensity record between the oil leading edge and up to a point just prior to the third destructive interference band is used (see the upper-right-hand window shown in fig. 6). This usually results in the most accurate and most localized measurement of skin friction.

If only two points are used to define the line drawn on the image (steps 2 and 3 above), the line will be straight. For cases where the oil streamlines are curved, up to 6 points can be used to define a second-order curve that follows the streamline curvature of the oil. CXWIN4G will interrogate the second-order curve fit at the "Measurement location" specified in the "Data" dialog box to determine the skin friction vector direction.

In the "Data" dialog box, the user has a choice of specifying the location of the skin friction measurement to be at the leading edge of the oil or at a position at 3/4 the distance between the start and end of the portion of the intensity record used to find the fringe spacing (shown in green in the upper-right-hand window and on the image) or at a position midway between the first and second fringes. The location of the leading edge of the oil is determined by either a linear or quadratic fit of the height of the oil at the fringe locations. The quadratic fit is used when more than two fringes are included in the intensity distribution (as indicated by small vertical blue line segments shown in the upper-right-hand window). The leading edge position is printed to the log file and is the distance upstream of the first fringe (indicated with a negative sign).

In most cases, the user should choose the leading edge as the position attributed to an FISF measurement because the equations which govern the flow of oil on a surface are hyperbolic. It has been demonstrated that under low shear gradient conditions, the streamwise oil thickness variation is linear and the slope of the oil, near the leading edge, is governed solely by the flow upstream of the oil's leading edge; hence, the τ_w measured is the value at the leading edge location.

The intensity data along the line joining these two points will appear in the line plot window in the upper-right-hand child window. To see an enlarged version of this plot, click on the $\wedge$ located above this window. To return the plot window to its initial size, click on the $\wedge$ again.

The manner in which the intensity is determined at a point (that may or may not be coincident with a pixel center) involves linear interpolation of the four pixels surrounding the point of interest to create what are referred to as virtual pixels. Specifically, referring to figure 7, the four pixels surrounding x_{vir}, y_{vir} are interpolated to determine the intensity at points a, b, c and d. The intensity at these four points is then interpolated in the x and y directions to find two intensity values at x_{vir}, y_{vir} yielding two quantities I_x and I_y that are then averaged to give a value for the intensity at x_{vir}, y_{vir} .

To increase the accuracy of the intensity determination, one can choose to increase the thickness of the line drawn on the image (see "Data" dialog box). Line thickness of 2, 4 or 10 pixels wide can be selected. When a line thickness other than 2 is chosen, the interpolation process just described is

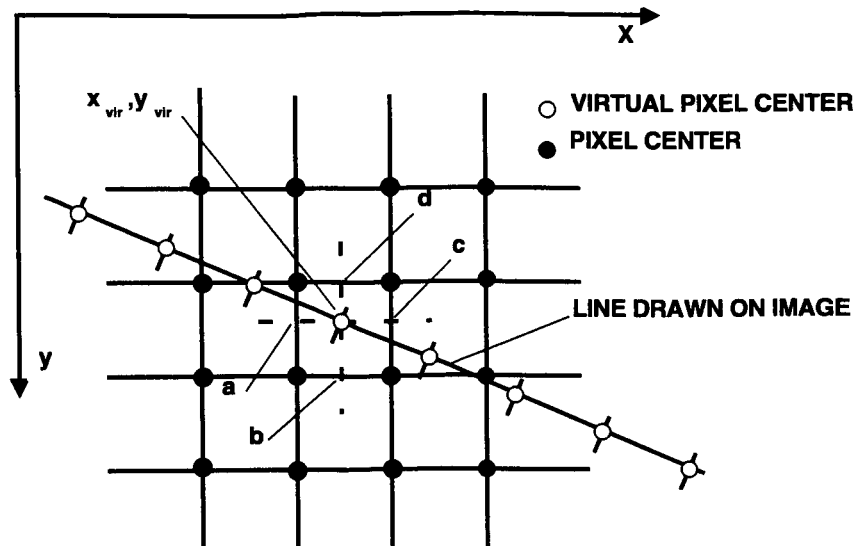


Figure 7. The nearest neighbors pixel averaging scheme.

repeated at virtual pixel locations chosen at points normal to the line drawn on the image. The additional intensity measurements are then averaged in a weighted average where the pixels closest to x_{vir}, y_{vir} have the greatest influence on the resultant intensity.

The theory behind this type of weighted averaging normal to the line drawn on the image is that the effect of noisy fringes will be averaged out, yet the phase of the fringes should be unaffected because the averaging is done along a direction that is parallel to the fringe fronts. It should be noted that accuracy gains using this type of averaging will only be realized for nominally straight fringe fronts. For curved fringes, a line thickness of 2 should be chosen in the "Data" dialog box.

Measure the Fringe Spacing

The fringe spacing is determined through application of a nonlinear regression algorithm that has been specifically developed for interferometry. It should be noted that the FISF images should not be processed (filtered, equalized...etc.) in any way prior to running CXWIN4G. The nonlinear regression is capable of dealing with noisy images and additional processing may degrade the accuracy.

IV. Find the fringe spacing (in pixels).

1. Click on the **Find Cf** button at the top of the main window and the fringe spacing (in pixels) will appear in the lower-right child window.
2. If the regression results (shown in blue in the upper-right child window; see fig. 8) are acceptable, click on the **Db** button to store this particular measurement in the database.

The portion of the intensity record that is analyzed, using the nonlinear regression, is automatically determined by CXWIN4G. In fact, CXWIN4G applies the regression five times to intensity records of differing length and returns the results with the lowest error.

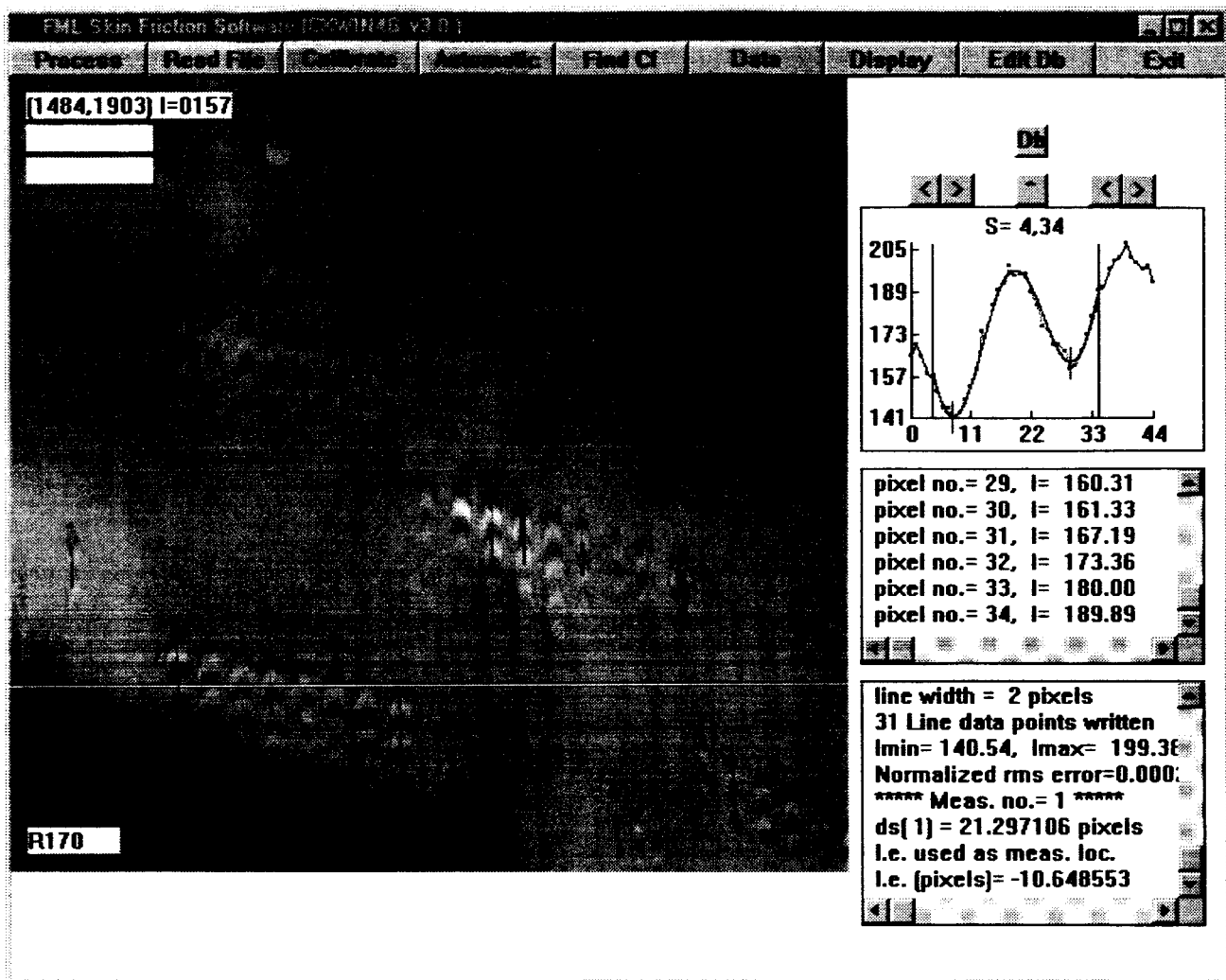


Figure 8. Regression of the intensity distribution (upper-right child window).

On occasion (particularly with noisy data), the nonlinear regression will get stuck in a local minimum and will not converge to the best solution. If CXWIN4G is not successful in its repeated regression attempts, this can be remedied by changing the number of points fed to the regression and then retrying (move the windowing bars one or two pixels, as discussed below, and then hit **Find Cf** again). It should be noted if **Find Cf** is depressed a second (or more) times, the regression is applied to the portion of the intensity record explicitly selected by the user via the intensity windowing controls. Thus, the user can force the regression to be applied only to the portion of the intensity record shown in the upper-right window thereby defeating the multiple regression attempt capability.

Two types of controls are provided to “window” the fringe intensity data. Gross control is achieved by clicking the right and left mouse buttons in the plot window to position the data limiting bars (right mouse button for the right bar and left mouse button for the left bar). Fine positioning can be done using the left-right arrows located above the plot. Use the plot window controls to position the data limiting bars so that they are approximately midway between the interference peaks upstream of the first destructive interference band (or fringe) and downstream of the second destructive interference band.

The results of the windowing process will be indicated on the image and in the plot window by a color change from red to green.

The purpose of windowing is to obtain the greatest accuracy and localization of the measurement possible through restricting the regression analysis to the first two fringes of a well resolved fringe pattern. Only in cases when fewer than a dozen pixels exist between the first and second fringes should the third fringe be used (see ref. 1).

The results of the skin friction measurement can be saved in an ASCII database file **disk:\expskin\data\default.bas** each time the **Db** button is hit following a valid measurement. When data is stored in the database, the application will draw a small blue square on the image at the x, y location that is attributed to the measurement (either the leading edge of the oil streak, the 3/4 point or 1/2 point as described previously). In addition, a blue line is drawn indicating the pixels that were used in the measurement (prior to data windowing). Superimposed on this blue line is a green line segment which shows the fringe spacing. This green line segment is drawn starting at the first pixel of the intensity record (upper-right child window) and the length of the green segment is equal to the fringe spacing to the nearest pixel. It should be noted that the actual fringe spacing used in the skin friction determination is of much higher accuracy because it comes from the nonlinear regression.

Steps III and IV should be repeated for all of the oil streaks in the image. Steps I and II should be performed for each new image read in.

An additional "automatic" fringe detection capability is currently under development that may be incorporated in later versions of the application. Essentially, this capability will be an alternative to performing steps III and IV and works best on isolated elongated oil streaks (i.e., from drops). The user will activate this capability by depressing the **Automatic** button at the top of screen while the image is in high-resolution mode. The user then positions the cursor between the first and second fringes and depresses the left mouse button. The application then applies various image processing algorithms to find the oil streak centerline and then determines the skin friction magnitude and direction. If the user is satisfied with the results, the measurement can then be added to the database by depressing the **Db** button. The user will be able to switch between high- and low-resolution modes in the usual way. The automatic mode can be exited at any point by depressing the right mouse button.

Process the Data

In this step, the data stored in the **default.bas** file is analyzed.

V. Apply the photogrammetric calibration to the measurements.

1. Click on the **Process** button at the top of the main window.

When the **Process** button is depressed, CXWIN4G reads the **default.bas** file and executes the photogrammetry and Delaunay triangulation modules and creates the **.fmt** files. An FISF image does not have to be displayed on the screen. In fact, this button can be hit anytime after a calibration has been completed and at least one skin friction measurement has been stored in the database. Often, data from many images are stored in a single **default.bas** file (i.e., multiple images from several tunnel runs

but under approximately the same tunnel run conditions). CXWIN4G will perform separate reductions of the skin friction measurements from each image and combine all of the results in a single Delaunay triangulation. The way that this is accomplished is that the **default.bas** file is searched for calibration data and when a calibration data set is located, this calibration data is used to reduce the skin friction data that is located between the end of this calibration set and the beginning of the next calibration data set.

If an image has been read and there is only one calibration data set in the **default.bas** file, CXWIN4G will use the photogrammetric transformation to calculate the x, y pixel locations corresponding to the X, Y, Z data in the **surfpts.dat** file. These “inverse” points are displayed as red squares on the image when the **Process** button is depressed. This is a useful check on the accuracy of the Direct Linear Transform (DLT) photogrammetric transformation.

On occasion, during the Delaunay triangulation, two measurement point locations are found to be too close together for the Delaunay algorithm to proceed. If this occurs, an error message will be printed to the **triangle.out** file giving the point number and the coordinates of the offending point. If this happens, the **Default.bas** file should be edited and the problematic point removed.

Display Results

CXWIN4G has a rudimentary results graphical display capability. The processed data is triangulated and then displayed in three popup windows. These windows show contours of skin friction, skin friction vectors and the unstructured grid resulting from the Delaunay triangulation.

VI. Display skin friction coefficient vector and contour plots.

1. Click on the **Display** button at the top of the main window and the “Graphic Display” dialog box will appear (see fig. 9).
2. Choose the type of contour plot desired and enter the number of contour levels, the vector scale factor...etc. Also, choose the plane of the view (either xy , xz or yz).
3. Click on **OK**.

Depressing the **Display** button initiates the graphics routines which display the skin friction results. CXWIN4G reads in all of the **.fmt** files created during step V and draws the results in several windows. The calibration points are shown as black squares on all of the plots and the auxiliary data points (the data in the **surfpts.dat** file) are shown as either red squares or pixels depending on the choice made in the “Graphic Display” dialog box.

The **rgb.dat** file is also read at this point. This file is an ASCII file of space separated values including an index followed by hue, red, green and blue values. (Note: the hue value is not used in the current version.) The hue, red, green and blue values are normalized. These colors are used by the contour drawing algorithm and can be one of several standard color schemes, the most common being a rainbow scheme. If the red, green and blue values are set equal to each other, a grayscale scheme is achieved. This file should contain a maximum of 236 entries.

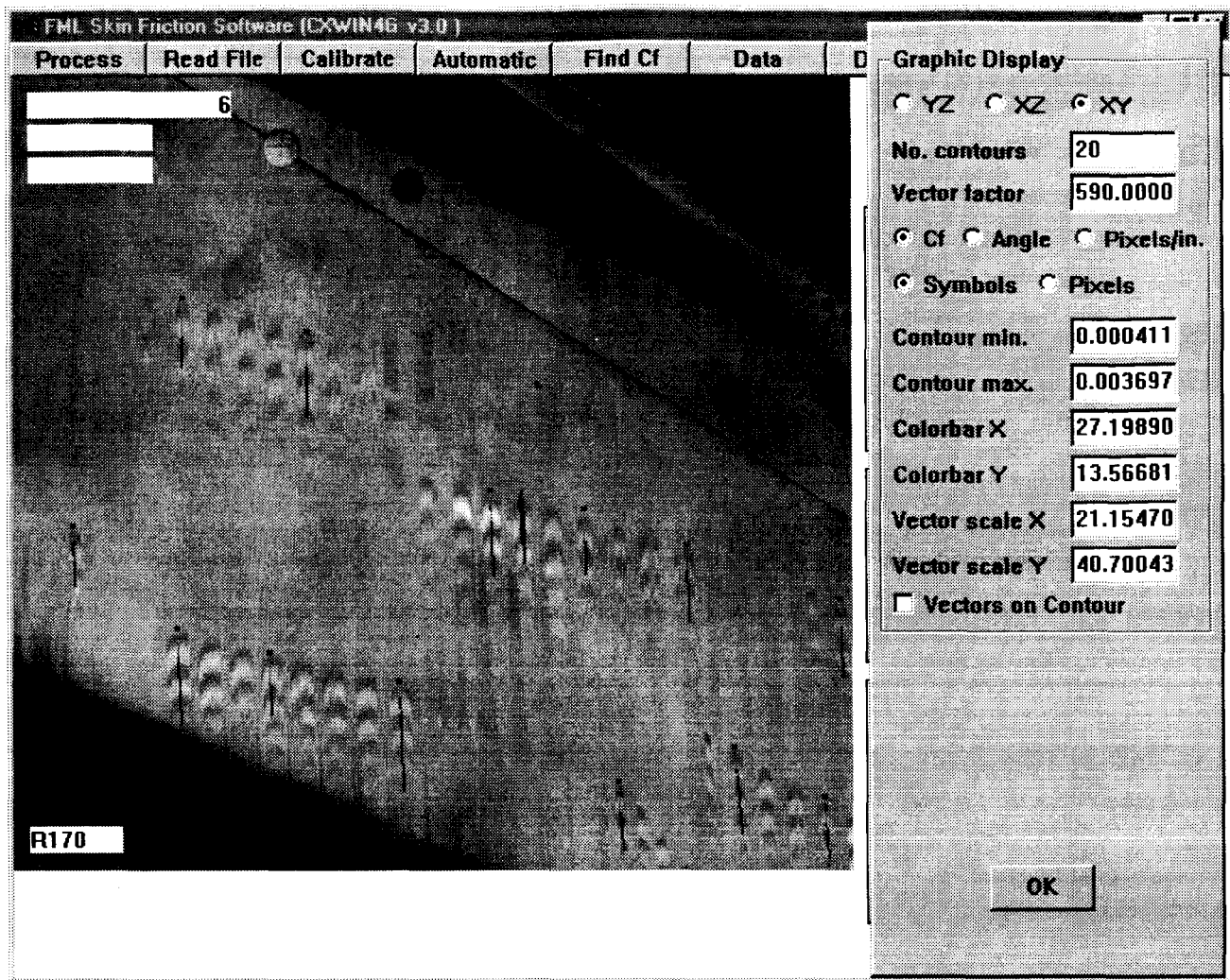


Figure 9. The “Graphic Display” dialog box.

The vector scale factor in the “Graphic Display” dialog box is simply a factor that can be modified so that the vectors, drawn in the graphic display, have a graphically pleasing length. By choosing a high number of contour levels (i.e., up to 236 levels), one can get a nearly continuous color distribution although this is computationally intensive. The display windows can be resized. The integer number shown in the upper-right-hand corner is a measure of the window height.

Examples of the graphics output capability of CXWIN4G are shown in figures 10–12. It should be noted that there is no perspective information in these figures. A three-dimensional graphics program such as FAST (ref. 6) should be used for this purpose. Also, some sort of screen capture program should be used to generate hard copy. Currently, CXWIN4G does not have a built-in print capability.

The main functions that CXWIN4G performs can be executed independently providing the sequence is the same as indicated by the Roman numerals in the steps previously discussed. For instance, occasionally, it is necessary to edit the **default.bas** file to remove points that appear to be erroneous when viewing the contour plots (can be caused by poor image signal to noise ratio, dirt specks, poor illumination,...etc.) and execute steps V and VI again. One may also desire to add or remove points

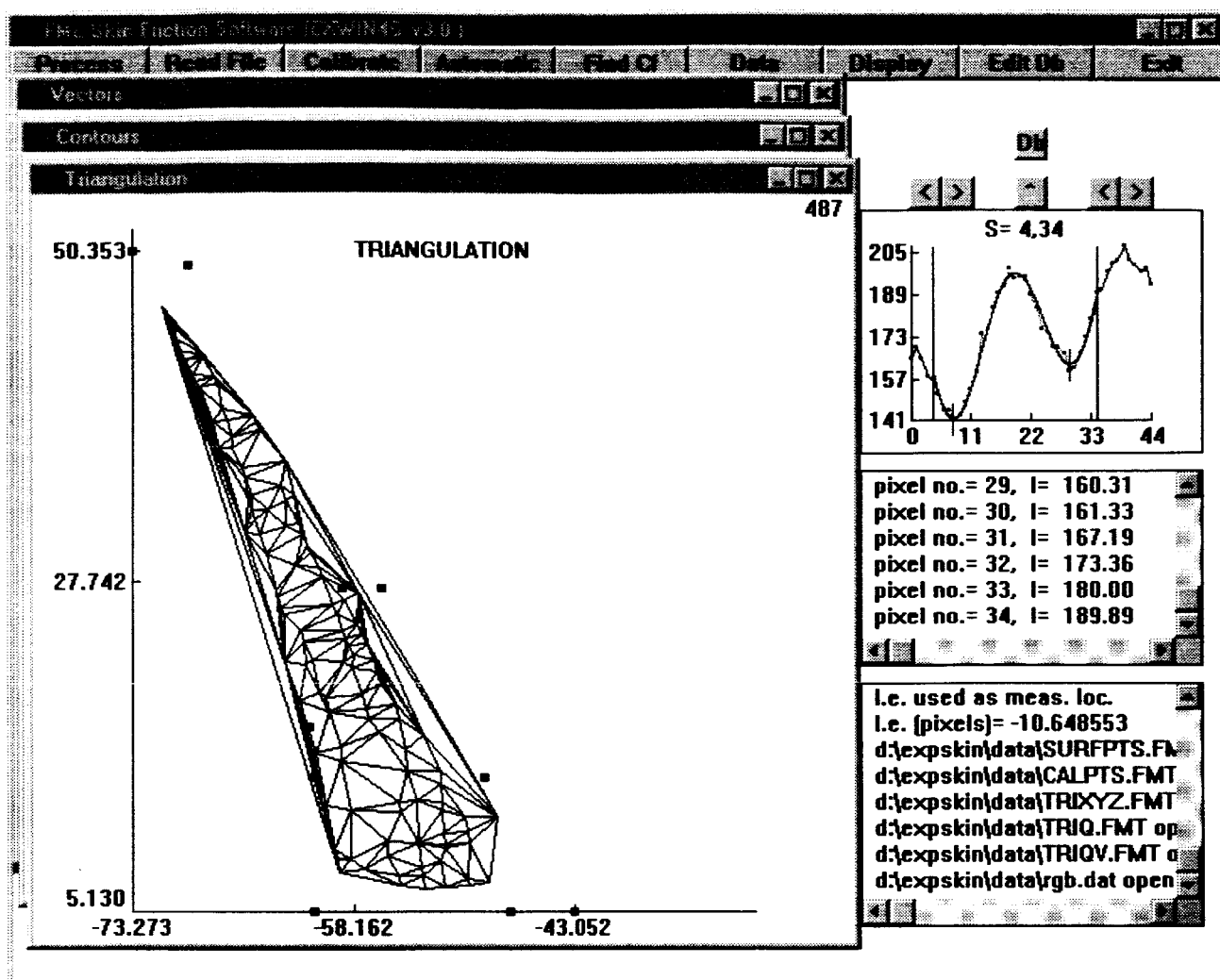


Figure 10. Delaunay triangulation display.

from **default.bas** in order to obtain a better Delaunay triangulation of the data (narrow triangles near edges can cause problems). If it is determined that inaccurate data was entered during the calibration, the errors can be corrected by editing the **default.bas** file and then repeating steps V and VI. When attempting to edit any of the files associated with CXWIN4G, be sure to exit CXWIN4G first. Also, a carriage return must be present at the end of the last line of all of the ASCII files read by CXWIN4G. When using editing applications such as Notepad and Wordpad, this carriage return must be entered manually.

Edit the Database

The **editDB** button can also be used to edit the **default.bas** file directly during a CXWIN4G session.

VII. Edit the **default.bas** file.

1. Click on the **editDB** button at the top of the main window.

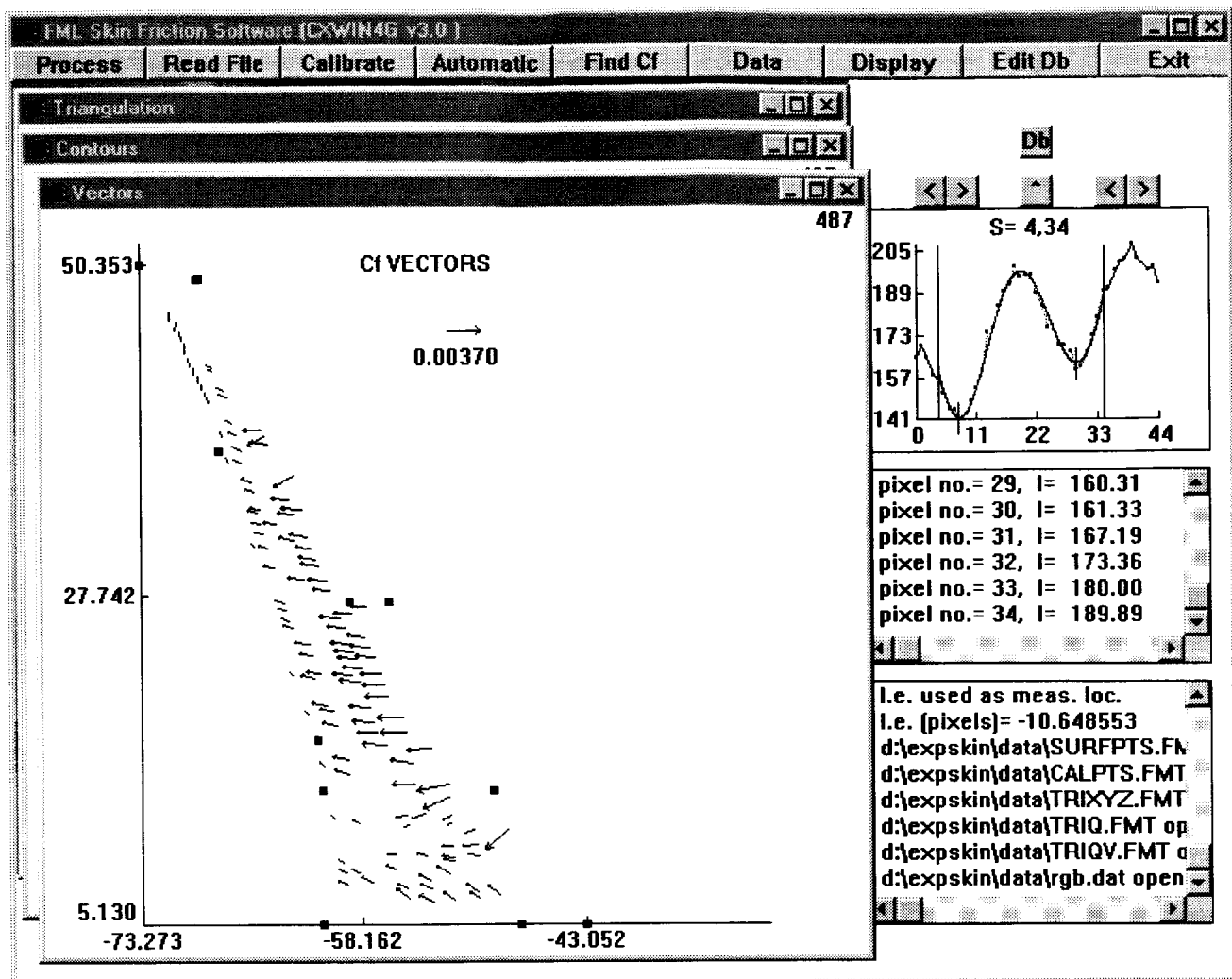


Figure 11. Skin friction vector display.

2. Position the cross cursor over the center of the blue box (or the red cross of a calibration point) associated with the datapoint to be removed and left-click.
3. Click on **OK** in response to the "Point turned off " popup box.

The **editDB** button doesn't actually destroy data. It simply places the characters " 'RM>' " at the beginning of the lines associated with the point to be turned off within the **default.bas** file. CXWIN4G will not include such points in future data processing or displaying. If so desired, a measurement can be reactivated by removal of the " 'RM>' " characters by editing the **default.bas** file directly.

Data Presentation

It is virtually impossible to apply oil drops to the surface of a wind tunnel model in a grid that is regular. The approach taken here was to put the oil down in a pseudo-random fashion and triangulate the skin friction data (using Delaunay triangulation; see ref. 7) extracted from the images and then to display the results using either the graphical capability of CXWIN4G or the "unstructured mesh"

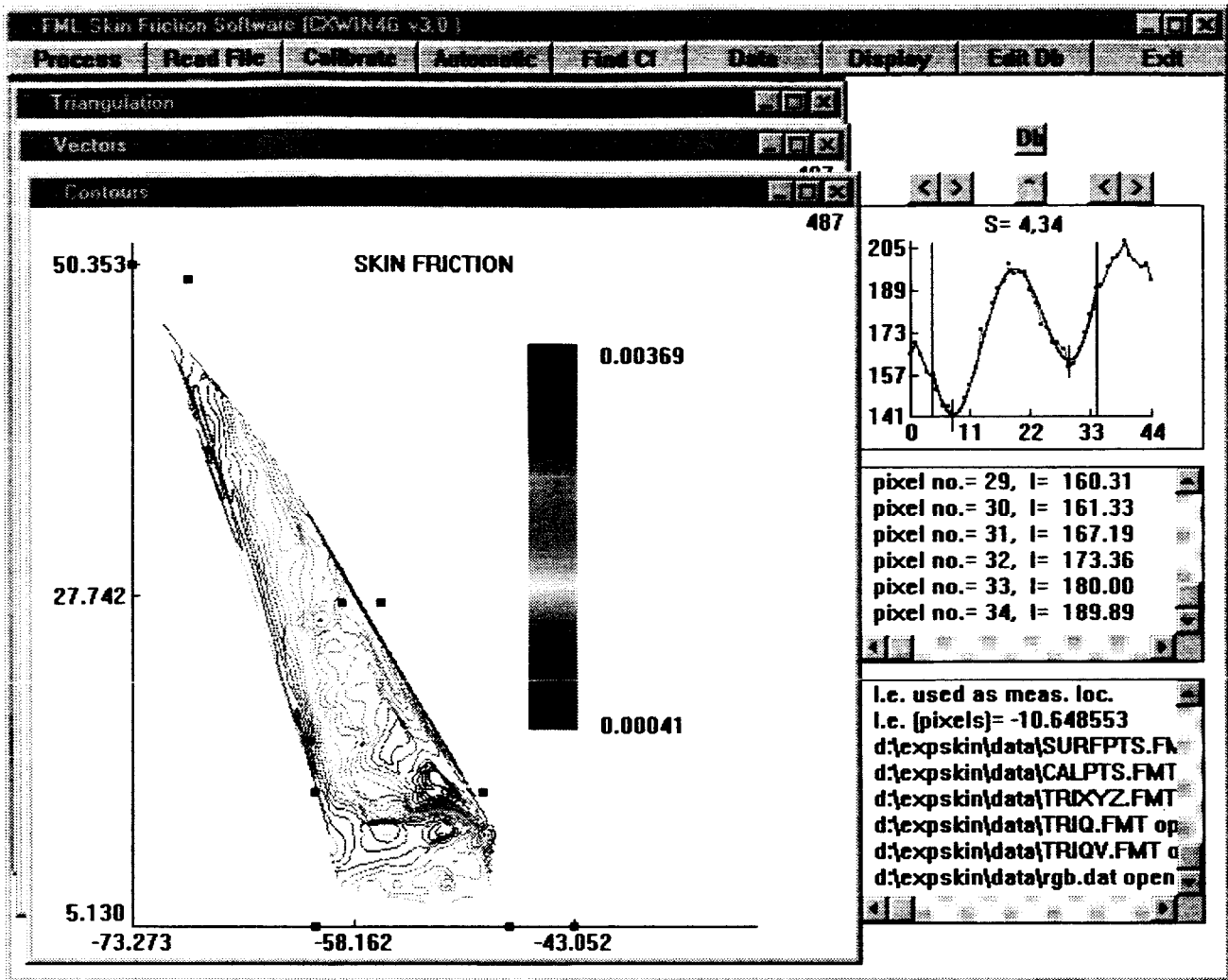


Figure 12. Skin friction contour display.

capability of FAST (ref. 6). This approach was found to be superior to interpolation of the skin friction data to a regular mesh prior to display.

Miscellaneous

1. Only grayscale TIF files should be read by CXWIN4G. In addition, the TIF files should not be LZW compressed. Photoshop or Paint Shop Pro can be used to convert color images to grayscale. The user should beware when using color cameras for FISF measurements because the pixel masking techniques, common to many color cameras, may result in noisy fringe intensity distributions.
2. Very large tif files can be read by CXWIN4G (up to width = 18432 × height = 17496 pixels) depending of the amount of RAM installed in the computer.
3. The j of i,j pixel nos. shown in the **default.bas** does not correspond directly to the numbers shown in the upper-left-hand corner of the image screen in that the j is typically 21 pixels greater in the **default.bas** file owing to space allotments for the window button controls.

4. CXWIN4G can be used without image calibration to determine fringe spacing in pixels but the **edit DB, Process, Display** and portions of the on-image fringe spacing display features will not be operable. These features require the presence of calibration data in the Default.bas file for the image being analyzed prior to invocation.

5. In some cases, it is desirable to use more than one image in FISF measurement. For instance, the tunnel startup and shutdown times may be so long as to introduce an unacceptable uncertainty level using only one image taken during or at the end of the run.

If images can be taken at two different times during the run, the C_f can be determined by measuring the rate of change of the oil height during the on-condition portion of the tunnel run. Using the two-exposure approach $C_f = \frac{2n_o\mu_o}{q_\infty\lambda}(d\Delta s/dt)\cos\theta_r$ where $d\Delta s/dt = (\Delta s_{t_2} - \Delta s_{t_1})/(t_2 - t_1)$. Although CXWIN4G was not designed specifically for this type of measurement, one can execute CXWIN4G separately for each of two images (use the same "Appended char." in the "Data" dialog box) to obtain two sets of fringe spacings. The locations of the FISF measurements of the first image will be superimposed on the second image when the second is read in. The **default.bas** file can then be read by a user supplied program and the above equation applied.

6. The silicon oil typically used in FISF measurements is Dow Corning 200 Fluid (Midland, MI). This fluid is a polydimethyl-siloxane polymer and is available with the physical properties listed in table 1. Some of these properties are hard coded into CXWIN4G. If other than Dow Corning 200 Fluid is used, the "(q/mu)dt" freestream properties option should be chosen because CXWIN4G does not require any hard-coded oil properties for this option.

When using other than the "(q/mu)dt" freestream properties option, the oil viscosity and density are determined at the temperature specified in the "Data" using the following expression:

$$\nu_{o,T} = \text{Exp}\left[\frac{C_1}{T + C_2} - \frac{C_1}{T_{cal} + C_2} + \text{LOG}_{10}(\nu_{o,cal})\right] \quad (3)$$

where T is in degrees kelvin, $C_1 = 774.8622$ and $C_2 = 2.6486$. This equation is most accurate for $255 \leq T \leq 310 \text{ K}$ ($0 \leq T \leq 100^\circ\text{F}$) and for $100 \leq \nu_{o,cal} \leq 1000$ and can be used to determine the nominal viscosity when ν_o is accurately known at temperatures other than 77°F (25°C).

Furthermore, the density of the oil is also slightly dependent on temperature. The manufacturer provides the following relationship for the oil's specific gravity at a temperature T :

$$\gamma_{o,T} = \frac{\gamma_{o,T=25^\circ\text{C}}}{1 + \alpha[T - 25]} \quad (4)$$

where the coefficient of expansion α is given in table 1 and T is in $^\circ\text{C}$. Hence $\rho_{o,T} = (\gamma_{o,T})\rho_{H_2O,T=25^\circ\text{C}}$ and determination of μ_o is a trivial task.

Table 1. Physical properties of Dow Corning 200 fluid.
(ref. 8, properties at 77°F or 25°C)

$\nu_{o,nom}$	cs	10	50	100	200	500	1000	10,000	30,000
γ	-	0.934	0.960	0.964	0.967	0.969	0.970	-	0.971
n	-	-	1.4022	1.4030	1.4032	1.4034	1.4035	1.4036	1.4037
α	$\frac{cc}{cc}/^{\circ}C$	0.00108	0.00104	0.00096	0.00096	0.00096	-	0.00096	0.00096

Listed in table 2 are the relevant software limits. These limits can be changed and the application recompiled as discussed in Appendix C.

Table 2. Software limits.

Maximum image size (TIF)	18432 width by 17496 height
Maximum number of calibration points	1000
Maximum number of points in the surfpts.dat file	1000
Maximum number of skin friction measurements	10000
Maximum number of pixels fed to the regression routine	1000
Maximum number of pixels in line drawn on image	6200
Maximum number of lines in the default.bas file	30000

CXWIN4G Error Codes

Error codes are reported to the lower-right-hand window and/or to the **.log** and **.out** files created by CXWIN4G. (If some aspect of CXWIN4G is not functioning as expected, be sure to check all of the **.out** files for error messages.) Table 3 summarizes the CXWIN4G error messages.

Known Bugs

1. When the application is busy with photogrammetry computations, the CXWIN4G window does not get properly repainted when it is activated. Upon completion of the photogrammetry computations, the window is repainted.
2. In Windows 95 and 98, CXWIN4G does not display the colors in the color contour plots correctly after the first time CXWIN4G is asked to repaint the contour plot. Use a screen capture program to capture the image prior to repainting.
3. CXWIN4G does not properly locate the camera position (and hence find the correct light angle θ_r) when the film plane of the camera is not approximately aligned with a plane of the model coordinate system.

User Feedback

Users of this application can use e-mail to send feedback to the author at gzillaic@mail.arc.nasa.gov. Of great interest are identified bugs, errors, omissions, desired new features...etc. An attempt will be made to pass on updates to those who correspond.

Table 3. CXWIN4G error codes.

IER	Description of the Error
Processed data display errors	
22	Error while attempting to plot the processed data to the screen.
62	Too few calibration points in the default.bas file.
444	Number of points exceeds array dimension in Delaunay triangulation.
224	Data points are too close together for Delaunay algorithm.
225	Triangulation attempted with too few points.
8	Stack array dimension exceeded in triangulation algorithm.
226	Error found while trying to locate a point during Delaunay triangulation.
Photogrammetry errors	
7	Array bounds exceeded in the least squares solver routine implying too many calibration points.
10	Error in the least squares solver.
16	Unable to locate camera.
35	Error in the photogrammetry portion of the code where the calibration is being used to find X, Y, Z .
44	Input data error while reading default.bas.
51	Cannot determine pixels/inch.
78	Cannot find a X, Y, Z point during application of the photogrammetry.
73	Cannot find the third coordinate during the interpolation of the auxillary data file or the calibration data set.
45	No skin friction unit vector could be found.
421	Too many duplicate points found either the calibration data or in the skin friction data.
38	Error finding X, Y, Z points in the vicinity of the point of interest.
36	Error finding the surface normal.
35	Error finding the light angle of reflection.
34	Cannot find a skin friction unit vector.
33	Cannot determine the pixels/inch.
95	Error initializing .fmt files or opening the default.bas file.
19	Undefined angle between camera and surface normal.
30	Light reflection angle greater than 90 degrees.
14	No surface normal found.
53	Too few valid points in auxiliary file.
322	Error interpolating the auxiliary surface file.
	Inverse photogrammetry error.
Scattered Data Interpolation Errors	
129	Less than 4 data points or 1 interpolation point in scattered data interpolation.
130	All data points are collinear in scattered data interpolation.
131	Data points are not all distinct.

APPENDIX A—INPUT/OUTPUT FILES

All of the files written and read by CXWIN4G reside in the **disk:\expskin\data** directory.

default.bas: This file is the ASCII database file. Prior to the first time CXWIN4G is run, this file should be present in the **disk:\expskin\data** directory. Use Notepad or some other method to create a new empty **default.bas** file. Data is added to this file when performing a calibration and when the **Db** button is depressed following a valid skin friction measurement. The data in this file is keyed by the "Appended char." entered in the "Data" dialog box. If the user exits CXWIN4G and then restarts the application, **default.bas** is searched to find data with the same "Appended char." label. If such data is found, it is displayed on the image as if the application had not been interrupted.

The same **default.bas** file can be used to store data from several different images (with the corresponding calibrations) provided all of the images are from the same test condition. It is a good idea to create a new **default.bas** file for each new test condition because the application uses all the data found in **default.bas** when computing the skin friction contours and plotting the C_f vectors. **default.bas** can be edited if necessary (to correct mistakes) but the basic structure of the file should remain unaltered. When CXWIN4G hunts for data in the **default.bas** file, it looks first for calibration data. If calibration data is located, CXWIN4G will use the first series of fringe spacing measurements, following the calibration data, for a given image. Hence, step II should be performed prior to step III or **default.bas** should be manually edited to move the calibration data to the correct location within the file if the steps are not followed in sequence. The following is a sample of the beginning of a **default.bas** file:

```
'C1>' 1 3694.000 3158.000 -69.52800 49.36790 2.071986 ' R170 '  
'C1>' 2 3765.000 3462.000 -73.27300 50.35290 2.090103 ' R170 '  
'C1>' 3 2777.000 3057.000 -68.04600 37.62500 2.934806 ' R170 '  
'C1>' 4 1228.000 2529.000 -61.21200 17.80060 4.619074 ' R170 '  
'C1>' 5 955.0000 2484.000 -60.83700 14.25890 5.086190 ' R170 '  
'C1>' 6 261.0000 2478.000 -60.83700 5.130200 6.543279 ' R170 '  
'C1>' 7 256.0000 789.000 -43.05200 5.130200 4.247795 ' R170 '  
'C1>' 8 259.0000 1211.000 -47.49890 5.130200 4.861328 ' R170 '  
'C1>' 9 955.0000 1253.000 -49.26200 14.25890 3.940729 ' R170 '  
'C1>' 10 2010.000 1953.000 -56.29078 27.24905 3.334009 ' R170 '  
'C1>' 11 2010.000 2169.000 -58.96000 27.24905 3.449271 ' R170 '  
'C2>' 3 -70.0 1.0 2048.0 2048.0
```

```
R170 Data written on Wed 4/08/98 12:28:22 AM  
'D1>' 946.00 0.000000 0.00 542.00 1.40 1.0000 1.00 69.50 0.00 0.00  
'D2>' 0.011106 25.976 ' constant, fringe spacing (pixels) '  
'D3>' 769.558 1247.096  
'D4>' 768.985 1247.870  
'D5>' 768.425 1248.650  
'D6>' 3 770 1246 760 1265 756 1285  
'D7>' 3 37
```

```

R170 Data written on   Wed  4/08/98    12:28:47 AM
'D1>'   946.00 0.000000   0.00 542.00 1.40  1.0000    1.00 69.50    0.00    0.00
'D2>'  0.011106    14.109   ' constant, fringe spacing (pixels) '
'D3>'   420.468 1313.743
'D4>'   420.986 1314.566
'D5>'   421.504 1315.389
'D6>'    2   420 1313    437 1340
'D7>'    4   29

```

The lines that start with “ 'C1>’ ” and “ 'C2>’ ” are calibration data. A calibration point entry has a point number, followed by an x,y pixel pair followed by the corresponding X,Y,Z in inches and concluding with “ ’ appended char ’ ” tag. The “ 'C2>’ ” line at the end of a calibration set specifies the coordinate direction followed by the distance of the camera (in inches) from the surface of the model, the value of the length scale used to scale the auxiliary data and the i,j pixel pair of the center pixel in the image. The lines that start with “ 'D1>’ ” through “ 'D7>’ ” are data from skin friction measurements. The “ 'D1>’ ” line contains the oil nominal kinematic viscosity in cs, the oil absolute viscosity in slugs/(ft sec), the oil density in kg/m^3 , light source wavelength in nm, oil index of refraction, the dynamic pressure in in. H_2O , the run time in sec, the temperature of the oil in $^\circ\text{F}$, followed by two numbers that are not used in the current version of CXWIN4GG. Some of the quantities on the “ 'D1>’ ” may be set to 0 or 1 depending on the options chosen in the “Data” dialog box. The “ 'D2>’ ” line contains the quantity $\frac{2n_o\mu_o}{q_\infty\lambda t}$ in units of 1/in. followed by the fringe spacing in pixels. The “ 'D3>’ ” through “ 'D5>’ ” lines contain three x,y pixel pairs that are points along the line drawn on the image near the measurement location. These points indicate the direction of the skin friction vector in pixel space. The “ 'D6>’ ” line contains the number of points used to define the line drawn on the image followed by the corresponding x,y pixel pairs. The “ 'D7>’ ” line contains the positions of the windowing bars used for this particular measurement. Note: All lines (i.e., records) with identifiers in the **default.bas** file must start with a space followed by the 3 character identifier (e.g., C1>) enclosed in single quotes.

These are the only essential lines in the **default.bas** file. Additional lines can be added as user comments provided that they are added following the “ 'D7>’ ” line (the calibration set and each particular measurement set should be contiguous).

Table 4 lists the files that CXWIN4G reads or creates during a typical session. All files with the **.fmt** extension are ASCII output files for use by PLOT3D or FAST. The format of these files is described in reference 6.

Table 4. I/O files associated with CXWIN4G.

Filename	Format	Contents
Input		
Default.dat	ASCII	Default data displayed in “Data” window on startup of CXWIN4G.
texpXXXXXXXXX.dat	ASCII	Data displayed in “Data” window corresponding to a particular case.
rgb.dat	ASCII	Colorbar data file for contour plots.
Output		
XXXXXXXXX.log		A log file of a CXWIN4G session.
ilerr.out	ASCII	ImgLib error output file.
photo.out	ASCII	Photogrammetry output file.
triangle.out	ASCII	Delaunay triangulation output file.
Photoxyz.fmt	Plot3d formatted/3d	X, Y, Z grid file containing measurement locations of the photogrammetry step.
Photoq.fmt	Plot3d formatted/3d	Q _{1–5} are C_f , X, Y and Z- C_f vector components and pixels/inch of the photogrammetry step (companion file to Photoxyz.fmt).
surfpts.fmt	Plot3d formatted/3d	X, Y, Z auxiliary data point file (used for plotting purposes only).
Calpts.fmt	Plot3d formatted/3d	X, Y, Z calibration data points (used for plotting purposes only).
Trixyz.fmt	Plot3d formatted/ unstructured	X, Y, Z grid file containing the Delaunay triangular grid.
Triq.fmt	Plot3d formatted	Q _{1–5} are C_f , pixels/inch, light reflection angle in deg., C_f and C_f (companion file to Trixyz.fmt).
Triv.fmt	Plot3d formatted	Q _{1–5} are C_f , X, Y and Z- C_f vector components and pixels/inch of the Delaunay triangulation step (companion file to Trixyz.fmt).
Input/Output		
Default.bas	ASCII	Data base file.

where XXXXXXXX above represent the “Appended char.” (maximum of 8) entered in the “Data” dialog box. Do not rename any of the above files as CXWIN4G looks for these specific filenames. A better practice is to create a separate folder for each different run condition and then rename the folder to **disk:\expskin\data** as required to run CXWIN4G.

APPENDIX B—PHOTOGRAMMETRY

One-Camera Photogrammetry

Photogrammetry is used to find the spatial locations of the skin friction measurements, the magnification of the system (pixels/inch) and also the angle of the light reflecting off of the oil on the surface of the wind tunnel model (for use in eq. (1)). A single-camera photogrammetry implementation is employed along with use of a 2-D Direct Linear Transformation (see ref. 9 for further information). No lens distortion corrections are applied. Since one-camera photogrammetry systems require additional information and/or assumptions, in order to extract depth information from an image, an auxiliary file (**surfpts.dat**), containing an accurate description of the wind tunnel model geometry in the X, Y, Z coordinate system (the same coordinate system as the calibration data), is read by the application and interpolated to find the depth. Additional specifics about the **surfpts.dat** file are given shortly.

The main assumption of the DLT method is that straight rays can be drawn from the model surface, passing through the image plane and meeting at the perspective center of the camera (see fig. 2). If, for example, one has an image of a surface taken by a camera that is viewing the X, Y plane, the collinearity equations relating the X, Y wind tunnel model coordinates to the x, y pixels can be written as follows:

$$\begin{bmatrix} x - x_o \\ y - y_o \end{bmatrix} = \lambda \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} X - X_o \\ Y - Y_o \end{bmatrix} \quad (5)$$

where m_{ij} are the elements of the transformation matrix, λ is a scale factor, x_o, y_o is the image coordinate of the principal point and X_o, Y_o and Z_o is the location of the perspective center in the model coordinate system. As seen in figure 2, x_o, y_o is the pixel located at the center of the image. The above equations can be recast into the following linear DLT equations:

$$x - x_o + \frac{L_1 X + L_2 Y + L_3}{L_7 X + L_8 Y + 1} = 0 \quad y - y_o + \frac{L_4 X + L_5 Y + L_6}{L_7 X + L_8 Y + 1} = 0 \quad (6)$$

where $L_{1...8}$ are functions of m_{ij} , X_o, Y_o , and λ .

During the photogrammetry calibration, the L coefficients are determined by using the X, Y and corresponding x, y of a minimum of four nonplanar reference points on the model. These points are applied to the $[a][x] = [b]$ form of the above equations. The resulting system of 8 or more equations and 8 unknown L coefficients is overdetermined (for more than the required minimum of four calibration points) and usually nearly singular. A Singular Value Decomposition (SVD) algorithm is used to solve this system in a least squares sense.

Once the L coefficients of the DLT transformation matrix have been computed the system is considered to be "calibrated." The collection of rays passing from the model through the x, y pixel space can be found, but without an additional equation (or a second camera), it is not possible to determine the position of the model surface along the rays.

An auxiliary ASCII datafile containing X, Y, Z datapoints (in column format) is used to provide additional geometrical information. The data in the auxiliary data file (**surfpts.dat**) are used to find the unknown third coordinate using the two coordinates that were obtained from the 2-D direct linear transform. At the X, Y location found using equation (6), a scattered data interpolation procedure (see ref. 10) is applied to determine Z .

The source of the **surfpts.dat** data can be a grid generated for CFD, CAD files, computations or analytical expressions describing the shape of the surface or simply the same calibration points used in the calibration process (provided that there are enough of them). The points in this ASCII auxiliary file must form a planar non-reentrant surface. In other words, all rays drawn from the perspective center of the camera can intercept the surface at only one point. In addition, the auxiliary points should completely enclose the area where the unknown X, Y, Z FISF locations reside, be in the same coordinate system as the calibration points (must be a right-handed system) and encompass the center pixel in the image (the pixel that the camera axis passes through; see fig. 2). The format of **surfpts.dat** is one X, Y, Z space-separated triplet per line and the data can be in any order and does not have to be regular.

If the wind tunnel model has multiple surfaces where FISF measurements are made, it is preferable to treat each surface individually (separate calibrations and **default.bas** files for each surface). CXWIN4G was not specifically designed to handle discontinuities in geometry so the user should start at step I for every new surface. The difficulty with multiple surfaces is that the scattered-data interpolation routine in CXWIN4G will use points from two different surfaces near a surface boundary, resulting in a blending of the surfaces.

Incident Light Angle

As mentioned previously, photogrammetry is also used to determine the light incidence angle required by the FISF technique (refer to eq. (1)). The light incidence angle (θ_i) is dependent on the orientation of the surface of the model, the position of the camera relative to the model and indirectly on the optics of the camera lens.

A normal to the surface at a X, Y, Z point of interest can be found by constructing a triangular surface plane, using points (located by photogrammetry) in the vicinity of X, Y, Z , followed by taking the gradient of the equation which describes the triangular surface plane. If the vertices of the surface triangle are denoted by X_1, Y_1, Z_1 , X_2, Y_2, Z_2 and X_3, Y_3, Z_3 respectively, then the equation of the plane containing the FISF measurement is of the form:

$$f(X, Y, Z) = AX + BY + CZ = AX_1 + BY_1 + CZ_1$$

where

$$A = (Y_2 - Y_1)(Z_3 - Z_1) - (Z_2 - Z_1)(Y_3 - Y_1)$$

$$B = -(X_2 - X_1)(Z_3 - Z_1) + (Z_2 - Z_1)(X_3 - X_1)$$

$$C = (X_2 - X_1)(Y_3 - Y_1) - (Y_2 - Y_1)(X_3 - X_1)$$

The accuracy of the above linear surface equation is dependent on the degree to which the points in the auxiliary surface geometry file accurately represent the level of surface curvature. The unit surface normal is given by:

$$\vec{n} = \frac{\nabla f}{|\nabla f|} = \frac{A\vec{i} + B\vec{j} + C\vec{k}}{\sqrt{A^2 + B^2 + C^2}} \quad (7)$$

The camera location (X_o, Y_o, Z_o) can be found by using the DLT equations and some additional approximations. This process is commonly referred to as resection. If the camera axis is most closely aligned with the the Z direction, for example, X_o, Y_o, Z_o can be found by using equation (6) with the assumption that the optical axis passes through the center pixel x_o, y_o of the CCD (see fig. 2).

The angle θ , which is the angle between the surface normal and the chief ray that the camera lens sees, is equal to θ_i since the light is being specularly reflected off of the oil and the model surface. If it is assumed that the chief ray, reflected from the oil surface, passes through the front node of the lens unbent by the optics, then calculation of θ (and hence θ_i which must equal θ) is straightforward.

The pixels/inch at a point on the surface are determined by application of photogrammetry to pixels in the vicinity of the X, Y, Z point of interest. The user of CXWIN4G should visually evaluate the pixels/inch and light angle distributions by selecting these options in the "Graphic Display" dialog box. Obviously, if the model's surface is smoothly varying and the surface is evenly illuminated, the pixels/inch and light angle distributions should be smooth and continuous. If the contours of these quantities are not smooth and continuous then either too few calibration points were used and/or too few points were contained in the auxiliary file (**surfpts.dat**).

APPENDIX C—MODIFYING AND RECOMPILING CXWIN4G

CXWIN4G is a mixed language application that was developed using Microsoft Visual C++ version 4.0 and Digital Visual Fortran version 5.0 on a 486 class machine running Windows NT version 4.0 and also on a second computer running Windows 95. Several of the subroutines used were developed by others as detailed in Appendix D.

The main program, TIF file reader, and some of the graphical display functions are coded in ANSI C. The nonlinear regression, photogrammetry, Delaunay triangulation and contouring routines are coded in Fortran 77 and called by the C main program.

In the event that recompilation of any of the CXWIN4G C modules becomes necessary, the recompiled C modules can be linked with the Fortran object modules provided on the disk, hence no Fortran compiler would be required. If any of the Fortran modules need to be recompiled, the Visual Fortran project CXFMOD can be compiled and the appropriate object modules moved to the CXWIN4G project file folder. The **CXWIN4G.mak** file included on the CD ROM shows the necessary C compiler options required to recompile and link the application.

APPENDIX D—SOFTWARE SOURCES USED IN CXWIN4G

Approximately half of the CXWIN4G source code was written by the author of this user manual and the rest was obtained (with permission) from the following sources:

Delaunay Triangulation: The Delaunay triangulation routine was extracted from the GEOM-PACK software package (version 3) written in Fortran by Barry Joe (ref. 7). The routines in this package are written in Fortran 77 and are available via anonymous ftp from [menaik.cs.ualberta.ca](ftp://menaik.cs.ualberta.ca) in the `pub/geompack` directory.

TIF File Reader: `ImgLib` (version 1.25) is a 32-bit royalty-free shareware DLL written in C for developers who would like to support reading, converting, and manipulating of all popular graphics image formats like BMP, JPEG, TIFF, PCX, Photo CD, and others. `ImgLib` is available at: <ftp://ftp.netcom.com/pub/si/simsoft/ImgLib> `ImgLib` Copyright (c) 1994-1996 SimSoft. `Xli` Copyright (c) 1989, 1990, 1991, 1992, 1993 Jim Frost, Graeme Gill and others. `TIFF Library` Copyright (c) 1988, 1989, 1990, 1991, 1992, 1993, 1994 Sam Leffler Copyright (c) 1991, 1992, 1993, 1994 Silicon Graphics, Inc.

Nonlinear Regression Routine: `QNMDIF` is written in Fortran 77 and uses a quasi-Newton method, with difference approximations to derivatives, to minimize a nonlinear function $F(X)$ of the n independent variables $X_1, X_2, \dots, X_n$. The method is iterative and intended for functions which are continuous and have continuous first and second derivatives although it does function when occasional discontinuities are present (see ref. 11).

Scattered Data Interpolation Routine: The scattered data interpolation routine uses triangularization and 2-D splines to perform two-dimensional data interpolation (fit plus evaluation) for irregular data. The software was obtained from reference 11 and is written in Fortran.

Contour Plotting Routine: Subroutine `TRICP` is a Fortran routine written by A. Preusser that uses the results of a Delaunay triangulation of data to produce smooth contour lines by computing the intersection of the contour levels with quintic polynomials. The source of the triangle-based contour Plot Program is the ACM collected algorithms (ACM 626, see ref. 12). Copyright 1998 Association for Computing Machinery, Inc.

SDV Routine: The source of `SGELS`, the Single Value Decomposition routine, is `LAPACK` (version 2.0) which can be obtained from <http://www.netlib.org/lapack>.

APPENDIX E—QUICK START TUTORIAL

Included with the software is a sample image of FISF measurements on a commercial transport wing. For new users, the following is a brief tutorial designed to give a user an introduction to CXWIN4G.

1. Copy the **expskin** folder to the top level of the hard disk.
2. Left-double click on the CXWIN4G icon.
3. Left-click on the **Read File** button in the main CXWIN4G window.
4. Enter R170 in the “Appended char.” field.
5. Click on **OK**.
6. Left-double click on the R170-1647 TIF image file in the “Read an Image From a File” popup dialog box.
7. Center the red box over a portion of the wing and click on the center mouse button (or hit **Esc** for a two-button mouse).
8. Pick an oil streak and place the cursor upstream of the first fringe and left-click.
9. Move the cursor to a point downstream of the second fringe and left-click.
10. Right-click and the intensity distribution (along the line drawn on the image) should appear in the upper-right child window.
11. Click on the **Find Cf** button at the top of the main window and the fringe spacing (ds(1), in pixels) will appear in the lower-right child window.
12. Click on the **Process** button at the top of the main window.
13. Click on **OK** in response to the CXWIN4G popup dialog box.
14. Click on the **Display** button at the top of the main window.
15. Click on **OK** in the Graphic Display dialog box.

At this point, three overlapped windows should be present showing skin friction contours, skin friction vectors and the Delaunay triangulation used by the contouring algorithm. In the current example, 11 photogrammetry calibration points and 120 skin friction data points acquired previously are displayed. Not included in the above tutorial is image calibration or how to add a new measurement to the database. The reader should refer to the body of this manual for information on these topics.

REFERENCES

1. Ziliac, G. G.: Further Developments of the Fringe-Imaging Skin Friction Technique, NASA TM-110425, Dec. 1996.
2. Monson, D. J.; and Mateer, G. G.: Boundary-Layer Transition and Global Skin Friction Measurements with an Oil-Fringe Imaging Technique, SAE 932550, Aerotech '93, Costa Mesa, CA, Sept. 27-30, 1993.
3. Tanner, L. H.; and Blows, L. G.: A Study of the Motion of Oil Films on Surfaces in Air Flow, with Application to the Measurement of Skin Friction, *J. Physics E*, vol. 9, 1976, pp. 194-202.
4. Driver, D. M.: Application of Oil Film Interferometry Skin-Friction to Large Wind Tunnels, AGARD CP-601, Paper no. 25, Sept. 1997.
5. Schemm, J. B.; and Vest, C. M.: Fringe Pattern Recognition and Interpolation Using Nonlinear Regression Analysis, *Applied Optics*, vol. 22, no. 18, 1983, pp. 2850-2853.
6. Walatka, P. P.; Plessel, T.; McCabe, R. K.; Clucas, J.; and Elson, P. A.: FAST User's Manual, NASA Internal Report, Sept. 1991.
7. Joe, B.: GEOMPACK User's Guide, Dept of Computing Science, U. of Alberta, July 1993.
8. Information About Dow Corning Silicon Fluids, Dow Corning Corp., Midland, MI, 1994.
9. Marzan, G. T.; and Karara, H. M.: Rational Design for Close-Range Photogrammetry, UILU-ENG-76-2001, 1976, p. 1-223.
10. Akima, H.: A Method of Bivariate Interpolation and Smooth Surface Fitting for Irregularly Distributed Data Points, *ACM Trans. Math Software*, vol. 2, June 1978, p. 148.
11. Saunders, D. A.; Kennelly, R. A.; and Kennelly, L. C.: Aerodynamics Division Software Library, NASA RP-1276, June 1992.
12. Preusser, A.: Computing Contours by Successive Solution of Quintic Polynomial Equations, ACM TOMS, vol 10, no. 4, Dec. 1984.

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 1999	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE The Fringe-Imaging Skin Friction Technique PC Application User's Manual			5. FUNDING NUMBERS 519-20-22	
6. AUTHOR(S) Gregory G. Ziliac				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Ames Research Center Moffett Field, CA 94035-1000			8. PERFORMING ORGANIZATION REPORT NUMBER A-99V0036	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA/TM-1999-208794	
11. SUPPLEMENTARY NOTES Point of Contact: Gregory G. Ziliac, Ames Research Center, MS 260-1, Moffett Field, CA 94035-1000 (650) 604-3904, gziliac@mail.arc.nasa.gov				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified — Unlimited Subject Category 35 Availability: NASA CASI (301) 621-0390			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A personal computer application (CXWIN4G) has been written which greatly simplifies the task of extracting skin friction measurements from interferograms of oil flows on the surface of wind tunnel models. Images are first calibrated, using a novel approach to one-camera photogrammetry, to obtain accurate spatial information on surfaces with curvature. As part of the image calibration process, an auxiliary file containing the wind tunnel model geometry is used in conjunction with a two-dimensional direct linear transformation to relate the image plane to the physical (model) coordinates. The application then applies a nonlinear regression model to accurately determine the fringe spacing from interferometric intensity records as required by the Fringe Imaging Skin Friction (FISF) technique. The skin friction is found through application of a simple expression that makes use of lubrication theory to relate fringe spacing to skin friction.				
14. SUBJECT TERMS Interferometry, Skin friction, Photogrammetry, PC application			15. NUMBER OF PAGES 37	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	