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Imperfection and Thickness Measurement of Panels Using a Coordinate Measurement Machine

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Abstract

This paper summarizes the methodology used to measure imperfection and thickness variation for flat and curved panels using a Coordinate Measurement Machine (CMM) and the software program MeasPanel. The objective is to provide a reference document so that someone with a basic understanding of CMM operation can measure a panel with minimal training. Detailed information about both the measurement system setup and computer software is provided. Information is also provided about the format of the raw data, as well as how it is post-processed for use in finite-element analysis.

Introduction

In order for compression-loaded panels to be modeled accurately with finite-element analysis the geometry of the panels must be accurately measured and included in the model. Both flat and curved panels have been shown to sometimes be very sensitive to initial geometric imperfection and mismatches between the panel and fixture geometries (refs. 1-6). The Coordinate Measurement Machine (CMM) provides a very accurate means for measurement of panel geometry, and its programmability makes it useful for almost any panel configuration. Combining the data from a CMM with a user-programmable finite-element program, such as STAGS (STructural Analysis for General Shells) (ref. 7) creates an effective method for developing high-fidelity analysis models of structural panels.

Generally, panels are considered to have an idealized geometry; however, in practice, initial geometric imperfections are present in all structures. Geometric imperfection in panels refers to the deviation of the midplane of the panel from its ideal shape while in a stress free condition. This deviation can be caused by residual stresses created when the panel was formed, or it may be simply be due to the limitations in the accuracy of the manufacturing process. The effects of initial geometric imperfection on the buckling behavior of compression-loaded curved panels have been noted in the literature by a number of different authors (refs. 1-5). Geometric imperfection can easily be incorporated into most finite-element analysis models, provided it can be accurately measured.

Geometric imperfection creates addition problems for panels being mounted into test fixtures, because the panels must often be deformed in order to fit the fixture geometry. Fixtures for the testing of panels are generally designed to hold a panel fixed along the boundaries based on the ideal panel geometry. When imperfection causes the panel to deviate from the shape of the ideal panel along the boundary the process of clamping the panel into the fixture causes the panel to deform. At this point a typical panel will not only deviate from the ideal shape away from the boundaries, but also have internal stresses prior to being loaded. A parametric study by Hilburger et al. (ref. 6) examined the effect of placing compression-loaded panels with varying radii-of-curvature into a fixture with a fixed radius-of-curvature. The results showed that a wide variety of buckling and prebuckling behaviors could be obtained by varying the magnitude of the prestress.

In order to measure panel imperfection and thickness the Mechanics of Structures and Materials Branch at NASA Langley is using a Brown and Sharpe Global Image CMM, as shown in figure 1. The automation software that controls the CMM is PC-DMIS version 3.7 (ref. 8). The primary feature of this CMM is its ability to perform smooth, continuous scans across the surface of an object, thereby reducing the time required to obtain a detailed measurement of the surface contour. Since flat and cylindrically curved panels are of primary interest, a special purpose PC-DMIS program was developed by NASA to measure arbitrarily sized panels of these types. In addition to the PC-DMIS code, which actually controls the panel measurement, a Windows program MeasPanel was written by NASA to act as a Graphical User Interface (GUI) and provide an easy and convenient method for controlling the data input and output of PC-DMIS. By using MeasPanel it is possible for a user with only basic understanding of the operation of the CMM to measure panel imperfection and thickness, and create data files suitable for use in a finite-element analysis.

The objective of this document is to provide a detailed description of how to measure panels by using the CMM and the software program MeasPanel. First an overview of CMM measurement of panel imperfection is provided. Then information is presented on how a panel is defined in the CMM software for measurement. The panel alignment and scanning process are then described, followed by information on the post-processing of the panel measurement data. The descriptions provided herein should be sufficient for someone to define and measure a panel with the CMM, and process the data for use in a finite-element analysis program.

CMM Measurement Overview

The measuring of panels with the CMM machine requires three separate processes: panel definition, measurement, and post-processing. The panel definition and post-processing are done by the software program MeasPanel, while the actual panel measurement is performed in PC-DMIS. These three tasks will each be described in detail in this document, but first it is important to understand the coordinate systems used by the two programs.

Several different coordinate systems are used during the measurement and analysis of the panel. A curvilinear coordinate system is used to define the panel and also represents the coordinate system in which imperfection and thickness data is ultimately outputted. This coordinate system is shown in figure 2. The x-axis of the curvilinear panel coordinate system is along the axis of the panel and the z-axis is normal to the surface. The coordinate system origin is assumed to be at the center of the panel. The CMM machine and PC-DMIS use a rectangular coordinate system (figure 3) exclusively during panel measurement. All scan data going into and out of the PC-DMIS program is recorded in this coordinate system. During panel measurement the CMM measures four points on the inner surface of the panel and defines the X-axis to be oriented such that the points are best-fit by the curvilinear surface defined by the panel radius. The Y-axis is oriented along the direction defined by the top edge of the panel, perpendicular to the X-axis. Also during panel measurement the CMM measures the locations of the two side edges of the panel and uses the centerline between them to define the origin of the Y-axis. However, the measurement program does not assume that is always able to measure the bottom edge of the panel, and thus it infers the Z-axis origin using the location of the top of the panel and the user-defined panel height. Because of this inference, it is very important for the user to use accurate panel dimensions when defining the panel height. The Z-axis of the CMM rectangular coordinate system is assumed to be aligned parallel with the x-axis of the curvilinear panel coordinate system, and the origin of the curvilinear coordinate system is assumed to be located along the Z-axis of the CMM rectangular coordinate system based on the user-defined radius-of-curvature of the panel. During the post-processing, this data is converted back into the curvilinear coordinate system shown in figure 2.

The process of measuring a panel begins by running the Windows program MeasPanel. MeasPanel begins by starting PC-DMIS to ensure it is functioning properly. After that step is completed the user is taken to the main screen shown in figure 4. From this screen the user selects the panel to be measured and initiates the three separate processes of panel definition, measurement, and post-processing. Also on this screen the user can choose the file folder for data storage and create a new folder if necessary. If an already existing panel is selected from the Panel ID List, MeasPanel will display the status of whether the panel has been scanned and post-processed. For each panel, data is stored in multiple files that are all named using the Panel ID (*panelname*) as the prefix. The purpose of each of the individual files is discussed later and is summarized in Table 1. The three processes are described next.

Panel Definition

Selecting “Define/Edit Panel” button on the main screen of the MeasPanel program displays a window in which basic panel information and scanning requirements can be entered. The layout of this window is shown in figure 5. If no panel was selected from the Panel ID Listbox then the operator will be asked if he or she would like to create a new panel. If an already existing panel was highlighted in the Panel ID Listbox, then that panel’s information will be displayed. If the operator opens an existing panel and changes the name, then a new panel will be created and the existing panel’s data will remain unchanged. This allows the operator to easily duplicate data for similar panels. No data is saved until the operator selects the “Save & Exit” button at the bottom of the window. If a panel definition file already exists for the chosen name, then the program will ask the user if they want to overwrite the old file. By selecting this option all of the old data will be destroyed and replaced by the new panel information.

In order to create the panel definition file the operator needs the panel information listed below and illustrated in figure 6.

- Nominal height and width (arc-width for curved panels, maximum width if tapered)
- Nominal radius of the ideal panel (to the midplane of the wall) if curved
- Nominal wall thickness
- Panel taper ratio (width of bottom edge / width of top edge)
- Desired spacing of points, both vertically and circumferentially
- If the panel has a cutout, then the following info is needed

    Type of cutout (rectangular, circular, elliptical)

    Location of the center of the cutout relative to the center of the panel

    Vertical height of the cutout

    Width of the cutout (arclength). Obviously the same as the height for a circular cutout

    Orientation angle of the cutout in degrees

It should be noted that if a curved panel is chosen then the panel width inputted into the program must be the panel arc-width. It is possible to specify a taper ratio for a flat or curved panel. The taper ratio is defined as the arc-width of the bottom edge of the panel divided by the arc-width of the top edge of the panel. If a tapered panel is chosen then the panel width refers to the maximum width of the panel. It should also be noted that tapered curved panels are not conical sections, but rather tapered cylindrical sections (constant radius). As data is inputted into the panel definition window the sketch of the panel is updated. By selecting the “Show Points” button the operator can see the location of the scan points on the panel. This gives the operator a visual verification of the panel geometry. It should be noted that the sketch shows the view of the panel looking at the outer surface. This is very important if the cutout is not centered on the panel. The back-off distances limit how close the edges of the panel the scan lines are allowed. Since the panel must be griped at the sides during measurement the operator must ensure that the horizontal back-off distance is great enough to prevent the probe from contacting the support fixture.

Upon exiting the panel definition screen, the geometry information for the panel is stored in the file *panelname*`.def`. This information is used by PC-DMIS for alignment of the panel prior to measuring. A sample definition file is shown in Fig. 7. The layout of the definition file is fixed and does not change. Optional data such as cutout location still must stored in the file, but it simply does not get used if no cutout is selected. Detailed scan information, such as measurement point coordinates, for the inner and outer surfaces is stored in the files *panelname*`_iml.pts` and *panelname*`_oml.pts`, which are also used by PC-DMIS during panel measurement.

Panel measurement

The function of the PC-DMIS panel measurement program is to take the user-defined panel geometry and the desired scan paths, perform the measurements, and output the data to several files. In order to actually perform the measurement, the machine has to be aligned to the panel. Once the machine is aligned to the panel, it is then able to automatically perform all of the measurements required based on the data stored when the panel was defined. In addition to the alignment measurements, there are three sets of measurements that can be taken; inner surface scans, outer surface scans, and point measurements along the top and bottom edges. Data from these measurements are all outputted to separate files along with a file listing the alignment results.

Getting started

Prior to measurement the panel must be positioned on the CMM. The panel is mounted in a specially designed measurement stand that grips the panel at three or four points along the sides of the panel and holds the panel stationary while it is being measured. There are two reasons for having a special measurement stand, as opposed to using the test fixture. First, it allows access to a larger portion of the panel's surface, especially the areas where the knife edges and clamping plates contact the panel. Second, it allows the panel to be held and measured in its unconstrained shape. If the imperfections were measured while the panel was in the test fixture, then it would violate the mathematic definition of geometric imperfection, which is based on the stress free shape of the panel. There is almost always some mismatch between the panel and test fixture geometries, so the process of mounting the panel into the fixture results in some amount of panel deformation. As discussed in reference 6, the geometric mismatch between the panel and fixture can cause much greater changes in buckling load and nonlinear deformation than an imperfection of the same size and shape as the deviation from the perfect in-fixture geometry.

Prior to executing the program the panel should be place on the CMM with its inner surface facing towards the left side of the machine (see figure 8). The program will not function is a curved panel is oriented in another direction. The panel should be roughly in the middle of the machine and at least sixteen inches from the front of the CMM. If the top and bottom edges of the panel are to be measured, then the panel must be placed in a fixture that holds the panel up above the granite surface of the CMM. It is also important that the top of the panel extends up above the support fixture by at least an inch. This is because the PC-DMIS program must have access to the top outside corners of the panel during alignment. If a curved panel is being measured using the measurement stand, then the clamping knobs should be located on the outer side of the panel to create more room for the measurement probe. **The operator must be careful to endure that the CMM probe is clear to measure the surface of the panel without colliding with anything and that the specified back-off distances are sufficiently large enough for the probe to avoid the measurement stand grips.** The CMM probe should be a SP600M equipped with a 50mm extension and a 20mm by 4mm tip. This tool is labeled as CYLSP6 in PC-DMIS. The probe tip should be a spherical ruby for composite panels, and a Silicon-nitride tip should be used for aluminum panels. Newly assembled tools should be calibrated prior to panel scanning, and recalibrated on a regular basis if multiple panels are being scanned. For calibration procedures, see reference 8.

When the operator selects "Measure Panel" from the main window of the MeasPanel program a new window is displayed to allow the operator to specify detailed information about the type of measurements to be performed (figure 9). The operator can choose which surfaces of the panel are to be scanned and if the top and bottom edges are to be scanned. Also the operator must select the type of alignment to be performed. The choices are manual alignment, direct computer control (DCC) alignment, or measurement using the previous alignment. The operator can also select between analog (continuous) scans and stitch scans. For analog scans the probe is dragged along the surface of the panel, and for stitch scans individual points are measured. Analog scans are generally much faster and should be used unless surface features prevent their use. Once the operator selects the "Inspect" button, PC-DMIS is launched and measurement begins. The next step depends on what type of alignment was initially selected.

Manual alignment vs. DCC alignment

When the PC-DMIS program starts the measurement process, it reads in the nominal radius, height and width from the panel definition file, but it has no information about where this panel is located in three-dimensional space. In order to perform accurate measurements, the program needs a DCC (direct computer control) alignment, which accurately orients the coordinate system of the machine with the coordinate system used to define the panel geometry. The function of the manual alignment is a preliminary measurement to tell the program roughly where the panel is located in order for PC-DMIS to perform the more precise DCC alignment.

The objective of the manual alignment is to have the user to manually measure some points on the panel so that the program can calculate roughly where the panel is located on the machine and how it is oriented. The program will then orient its internal coordinate system to be aligned with the center of the panel as shown in figure 3. Manually measured points are not as accurate as points measured by the computer in DCC mode, so this alignment will only be used as a temporary alignment until the PC-DMIS program can measure a group of points around the panel and create a more refined alignment.

The most current alignment is stored in an external file, so it will be available, if needed, the next time the program is run. Thus, it is not mandatory to perform a new manual alignment or DCC alignment each time the program is executed. Obviously, if the same panel is being remeasured and has not been moved since the last time it was scanned, then it would not be necessary to perform the manual or DCC alignment again. In this case the operator could just select measurement using the previous alignment and the old alignment data will be used. The manual alignment does not have to be perfectly precise in order for the DCC alignment to work. Thus, it is sometimes possible to reuse the old manual alignment even if the panel has been slightly moved or if a different panel is being measured. The rule of thumb is as follows

> **A panel with the same nominal radius, height and width can be measured without a new manual alignment if it can be positioned on the machine within 0.1 in. of the location of the last manually aligned panel.**

The manual alignment process is not very difficult or time consuming, so if there is any doubt, a new manual alignment should be performed. A DCC alignment must always be performed on any new panel.

Manual alignment process

The manual alignment process is not difficult, but it is important to understand what data the program requires when it prompts the operator to measure certain points. If improper points are selected during the alignment process it is possible for the machine to crash the probe into something during the DCC alignment. During the manual alignment the operator is asked to measure points at a variety of locations on the panel and is given approximate coordinates for the measurements. The points do not have to be measured in exactly the specified locations and measurements in the vicinity of the specified coordinates are acceptable.

Both the manual and DCC alignments use points measured on the inner surface of the panel, and upon starting the CMM will rotate the probe head to 90°. The program first asks the operator to measure four points, one at a time, on the inner surface of the panel, as illustrated in figure 10. The points are used to define the orientation of the X-axis (see figure 3). Once these four points have been measured, the program asks the operator to measure an edge point on the top right of the panel. An edge point in PC-DMIS is a point that is used to represent a point on the corner formed by two planes, in this case the top edge and the inner surface. A manually measured edge point requires two measurements, first a hit on the surface of the panel and then a hit on the edge of the panel (figure 11). When prompted to measure an edge point, the operator must perform both measurement hits before pressing the "Done" button. The PC-DMIS program prompts the operator to measure two edge points on the top edge of the panel; first on the right side and then on the left side (figure 12). These two edge points are used to align the Y-axis and set the origin of the vertical axis based on the nominal height of the panel. The final step of the manual alignment process is for the operator to measure an edge point on each side of the panel near the top as shown in figure 13. The midpoint between these two points is used to define the origin of the Y-axis. Once these manual measurements are completed, the program will remeasure all of these points to verify their accuracy. The program will pause between each point so that the operator can ensure that the probe is clear to move and reduce the probe movement speed in order to verify that the CMM is measuring the correct points. This verification is important, because if the operator erroneously measures the wrong manual alignment points then the probe may collide with the panel while trying to remeasure points based on the erroneous coordinate system. Correct remeasurement of the manual alignment points implies that the coordinate system is defined accurately enough for PC-DMIS to perform the DCC alignment without the possibility of panel collision. Once the manual alignment is completed the program will automatically initiate the DCC alignment process.

DCC alignment process

The DCC alignment is an automated process in which the program measures a number of points on the panels inner surface and edges, and uses these points to orient its coordinate system. The alignment should be conducted for each new panel, regardless of whether or not the operator chooses to skip the manual alignment. The DCC alignment requires no operator action other than verifying that the probe is clear to move. If the manual alignment was not performed then the probe head should be positioned on the left side of the CMM facing the inner surface of the panel prior to starting.

The program will then measure four points on the surface and four points on edges in the same locations used for the manual alignment (see figure 10). The program performs a best-fit analysis fit to iteratively align the coordinate axes to the panel geometry. The program may cycle through all of the points more than once in order to achieve convergence. Following these measurements one point will be measured at the top of the panel in the center to check the radius-of-curvature of the panel.

Scanning

Immediately following DCC alignment the scanning process will commence. The top and bottom edges are scanned first, if the operator requested that an edge scan be performed. The edge scan gives the profile of the top and bottom loading edges of the panel at points spaced according to the defined circumferential point spacing. At each circumferential location, five points are measured to give the profile of the edge through the thickness. The data for both the top and bottom edges is stored in the file *panelname*`_EDGE.DAT`. The file contains the nominal X-Y coordinates of the inner surface at each circumferential point, the measured radius at that point, and the Z coordinate at the five points through the thickness.

Following the edge scan (if one was performed) the scans of the inner and outer surfaces of the panel are performed. The output of the scans will be stored in the output files *panelname*`_IMLPTS.CSV` and *panelname*`_OMLPTS.CSV`. These files contain the X-Y-Z coordinates and the I-J-K normal vector for each data point along the scan line. If an analog (continuous) scan was performed, then the circumferential spacing of these data points is based on a fixed PC-DMIS value of twenty points per inch and is not the user specified spacing. In this case, the output files must be post-processed in order to create data at the user specified circumferential spacing. The panel measurement process is now complete.

As a final step the PC-DMIS program will create an inspection report and save it as *panelname*`.pdf`. This inspection report gives data regarding the DCC alignment, the radius and geometry of the panel.

Post-processing

After the panel has been scanned, the measurement data can be post-processed to give initial geometric imperfection and thickness data for the panel. The output of the PC-DMIS program consists only of the measured locations of the scan points on the inner and outer panel surfaces defined in Cartesian coordinates. In order to obtain imperfection values, the scan data must be referenced to the ideal geometry. Thickness data is obtained by subtracting opposing scan points on the inner and outer surfaces, and eccentricity values are calculated based on a best fit mid-surface. The edge data is also post-processed to give the variation in flatness and slope along the loaded edges.

After selecting the button to process output on the main screen of MeasPanel, the post-processing window shown in figure 14 is displayed. However, if the panel is flat, or if only one side of the panel was scanned, then some of the options shown in figure 14 will not be displayed. These options allow the user to select which surfaces are processed and what to use as the reference surface which is compared to the ideal geometry in order to calculate the imperfection. The user also has the ability to control how the panel reference radius is defined. The panel radius defines the ideal geometry of the panel from which the imperfection is calculated. When the panel is processed the program will calculate the best fit radius for the panel. This best fit radius can be used as the reference radius or the user may specify a reference radius. For example, if the user was going the place the panel in a 60-in-radius fixture then the user may want to specify the reference radius to be 60 in. in order to determine how much deformation will occur when the panel is clamped into the fixture. The final option available allows the user to control an algorithm that calculates a best fit trigonometric series approximation for the panel imperfection. This algorithm filters out bad data points caused by surface irregularities that may not be representative of the panel imperfection. The trigonometric coefficients are based on the following equation

$$w_{imperfection} = \sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} \sin\left(\frac{i\pi x}{L}\right)\sin\left(\frac{j\pi y}{W}\right) + \sum_{i=0}^{n}\sum_{j=0}^{m} B_{ij} \cos\left(\frac{i\pi x}{L}\right)\cos\left(\frac{j\pi y}{W}\right)$$

where n and m represent the number of user-specified vertical modes and horizontal modes, respectively. The resulting sine and cosine coefficients are stored in the file *panelname*`_CMMfourier.dat`.

Once the appropriate options are chosen the user selects the "Process Data" button to begin post-processing. The post-processing of the CMM measurement data is conducted by an external program **`CMM2imp.exe`**. The objective of this program is to create a uniform grid, based on the user-defined scan spacing, that gives panel imperfection, thickness and eccentricity at each grid point. This grid data can then be used by finite element analysis codes to create an accurate finite element model of the measured panel. This grid data is stored in the file *panelname*`_CMM.dat`. This grid data is replicated in another file, *panelname*`_CMM.plt`, which is in Tecplot format. The edge imperfection data is stored in the file *panelname*`_CMM.uimp`, and the file *panelname*`_CMM.info` contains details and messages from the post-processing along with the best-fit radius and the average panel thickness. A panel can be processed again if the user chooses to, but old data files will be replaced by the new ones.

If the panel was defined as a curved panel, then there is also a button labeled "Check Radius." This button allows the user to obtain the best-fit radius information without creating all of the output files. Once the data has been processed, or if the user chooses to check the radius, the best-fit radius is displayed along with a profile of the panel radius from top to bottom. This profile is determined by calculating a best-fit radius for each individual scan line and displaying the result as a point on the graph. The labels at the bottom of the graph indicate the minimum and maximum radii-of-curvature.

Concluding Remarks

The combination of the PC-DMIS automation software and the Windows program MeasPanel allows a user to easily use a Coordinate Measurement Machine to measure imperfection and thickness of a flat or curved panel. The consistent format of the output files means that user-written subroutines can be created to combine the CMM data with a finite-element analysis program. By making it possible to easily use imperfection and thickness variation in finite-element analysis, it is expected that high-fidelity analysis of panels prior to experimental testing becomes more common.

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Table 1. Summary of Data Files

Data file	Purpose
panelname`.def`	Panel definition file
panelname`_iml.pts`	Nominal scan points for inner surface
panelname`_oml.pts`	Nominal scan points for outer surface
panelname`_IMLPTS.CSV`	Scan output data for inner surface
panelname`_OMLPTS.CSV`	Scan output data for outer surface
panelname`_EDGE.DAT`	Measurement output data for top and bottom edges
panelname`_CMM.dat`	Post-processed imperfection, thickness and eccentricity data for STAGS
panelname`_CMM.plt`	Post-processed imperfection, thickness and eccentricity data in Tecplot format
panelname`_CMM.uimp`	Post-processed edge imperfection data for STAGS
panelname`_CMMfourier.dat`	Post-processed imperfection data represented in trigonometric series format
panelname`_CMM.info`	Post-processing details, such as best-fit radius and average thickness

Figure 1. Brown & Sharpe Global Image CMM.

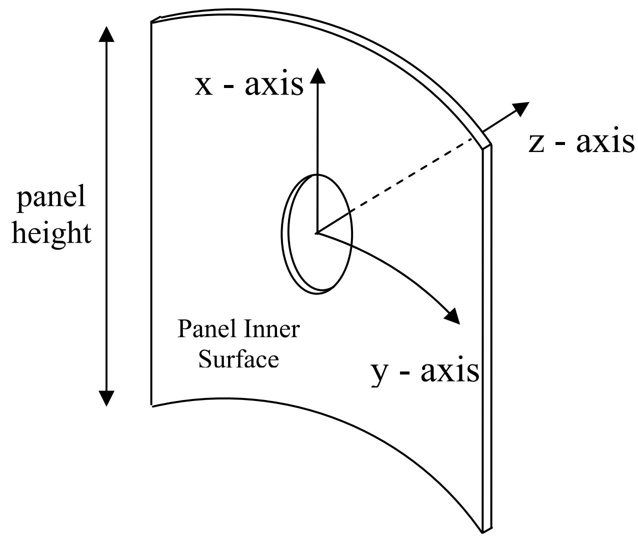

Figure 2. Coordinate system for panel analysis and data input.

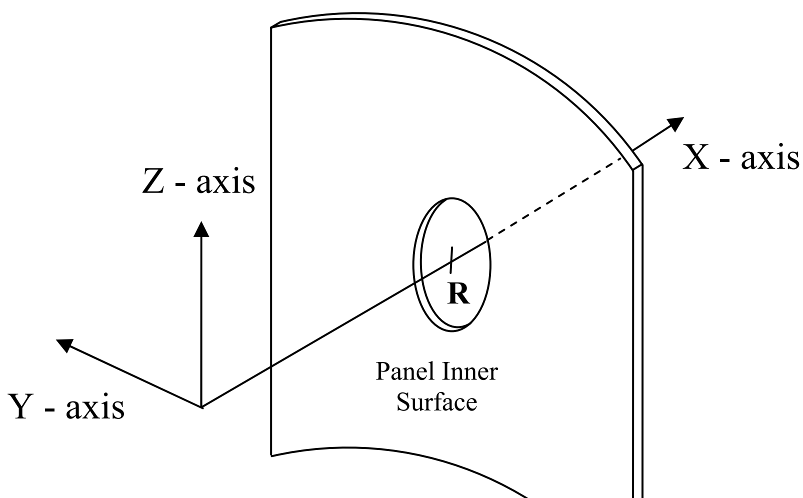

Figure 3. PC-DMIS coordinate system for panel measurement

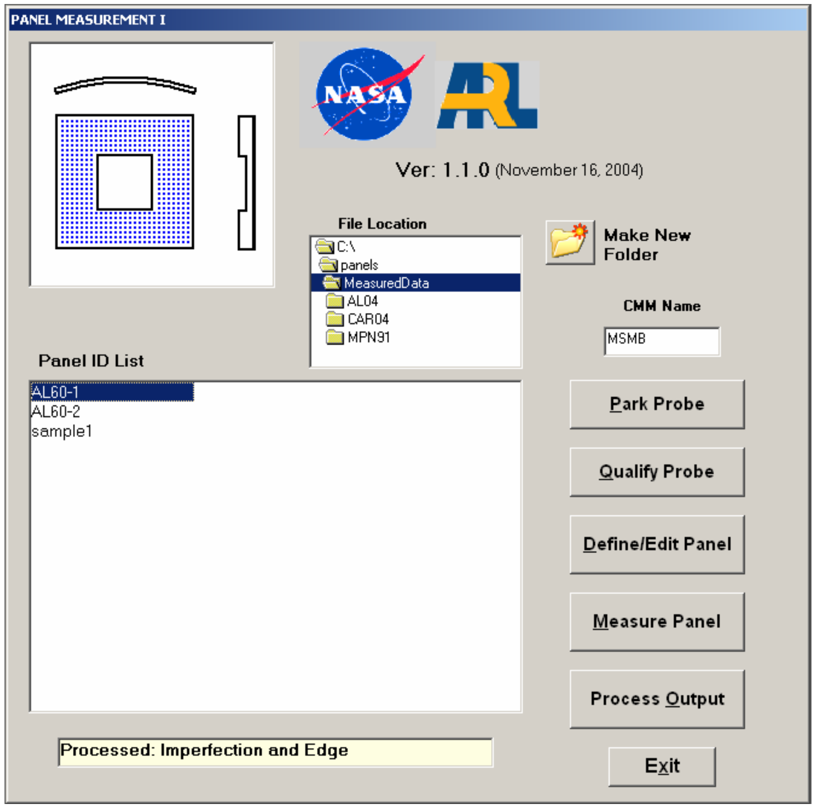

Figure 4. Main screen of the program MeasPanel.

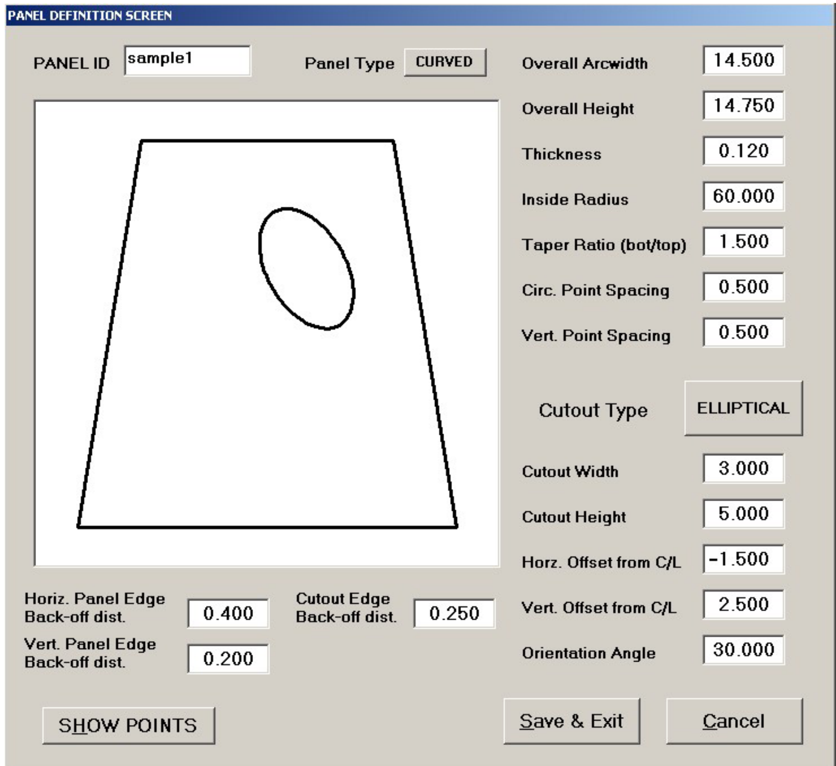

Figure 5. Panel definition window of MeasPanel.

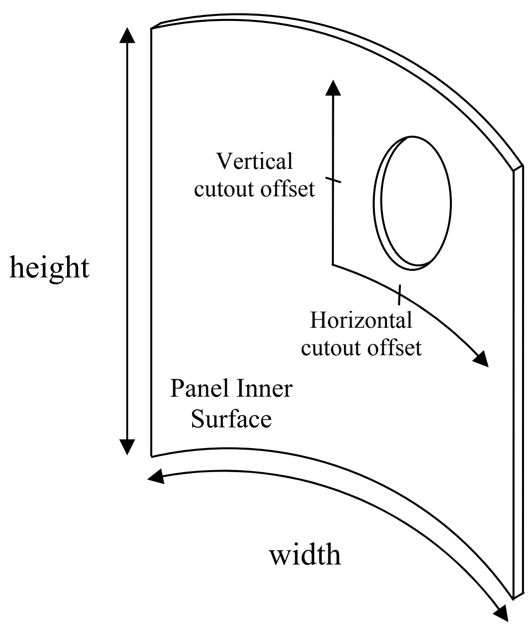

Figure 6. Panel geometry used to define a new panel.

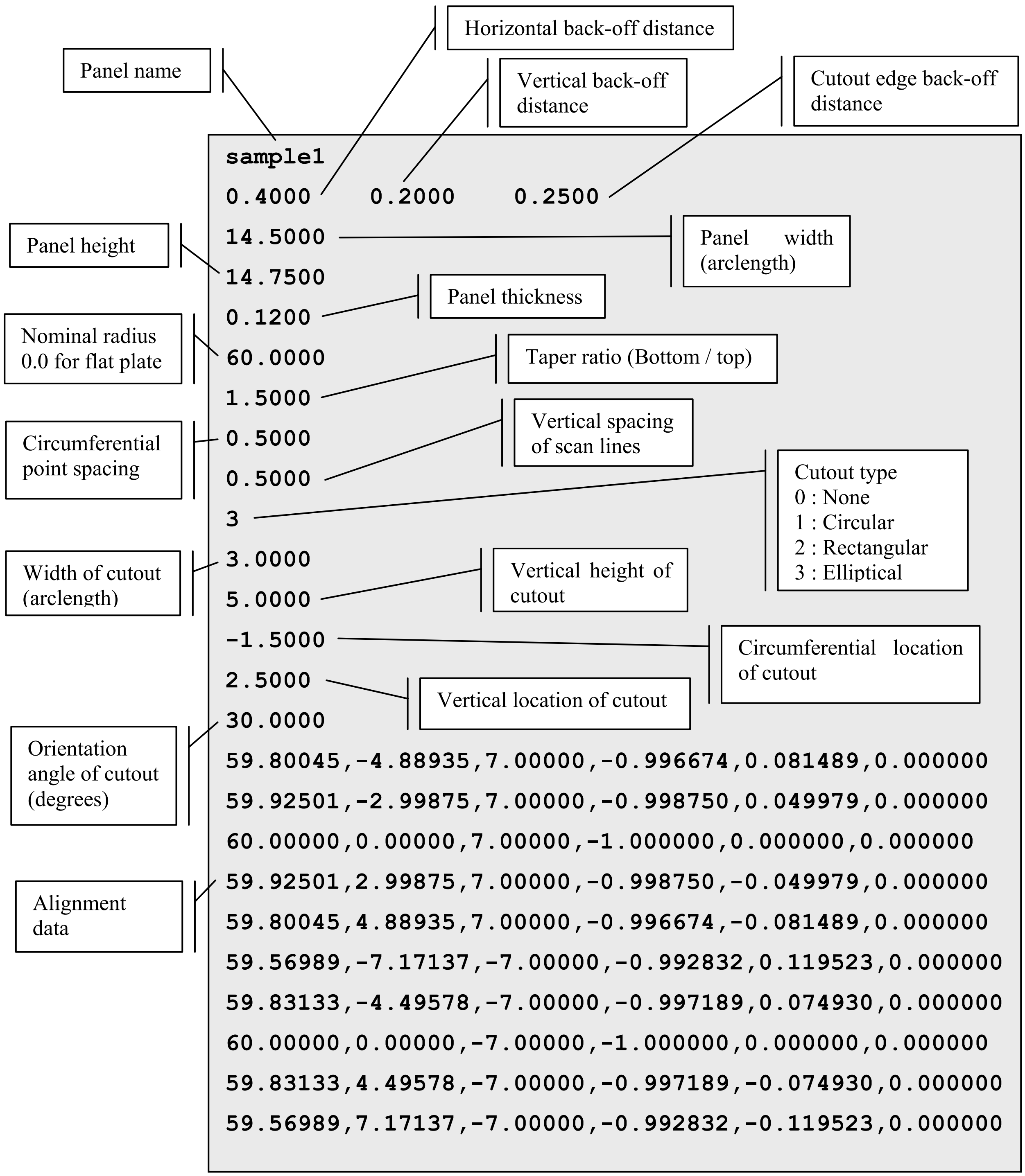

Figure 7. Sample format for the panel definition file, *panelname*`.def`

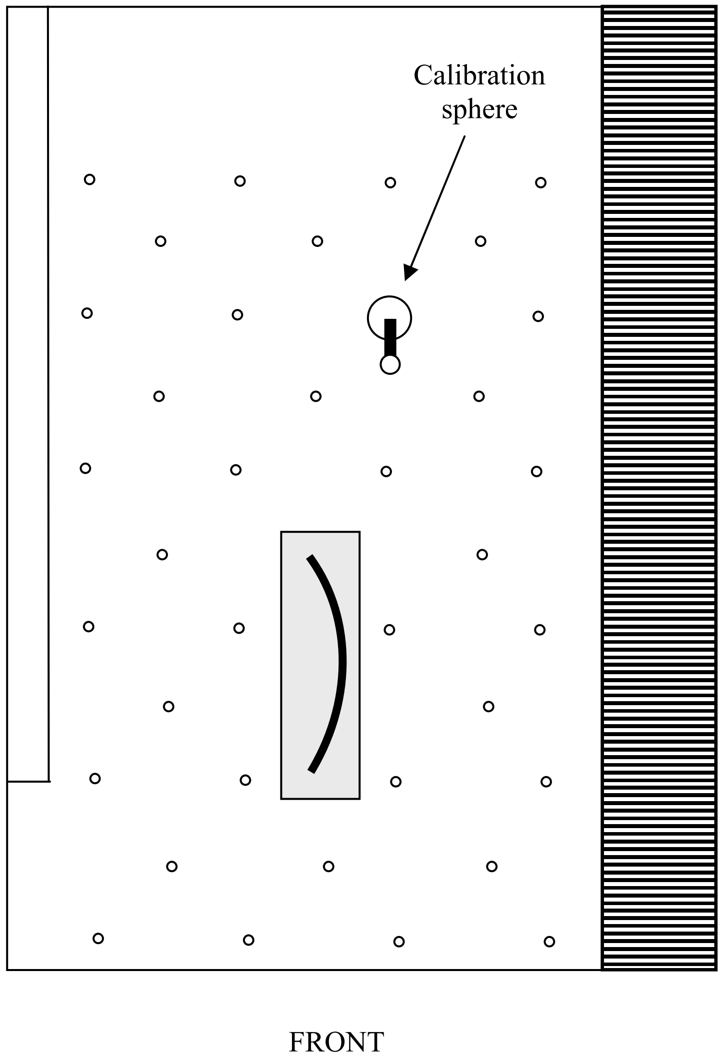

Figure 8. Setup for panel measurement on the CMM (top view of machine).

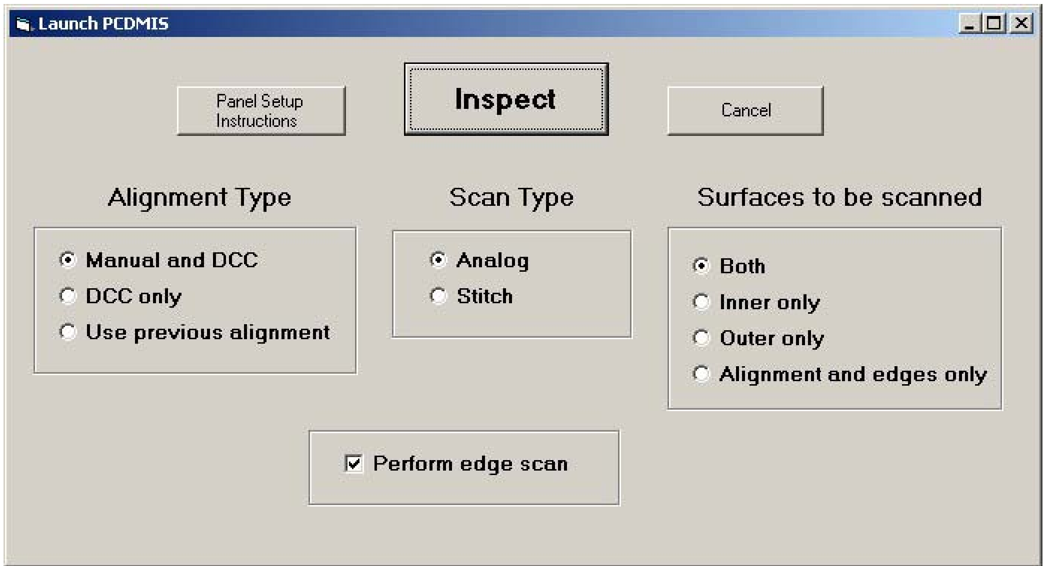

Figure 9. Panel scanning window in MeasPanel.

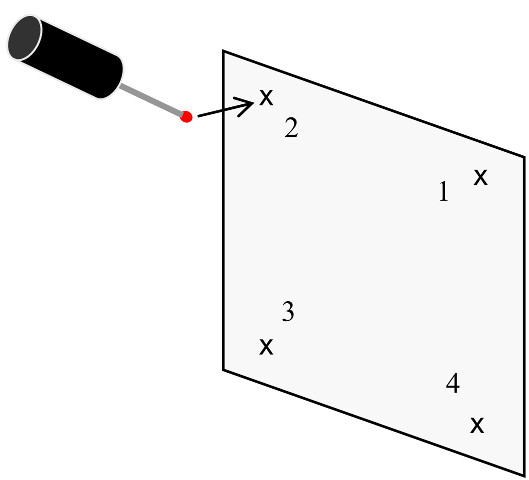

Figure 10. Illustration of the measurement locations on the inner surface of the panel during manual alignment and the order in which they are measured.

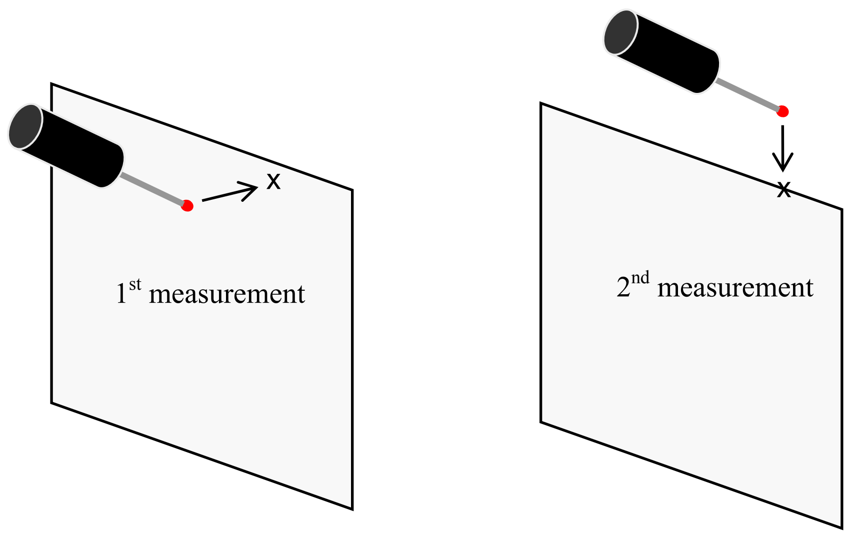

Figure 11. Example of the two measurements required to create an edge point.

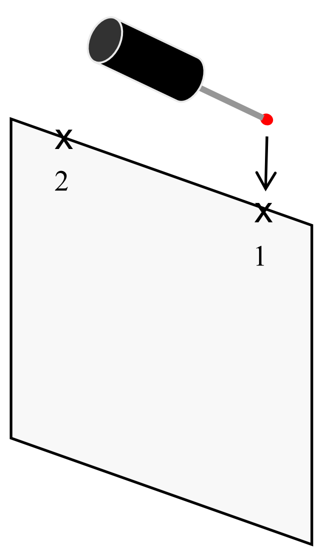

Figure 12. Illustration of the location of the top edge points measured during the manual alignment.

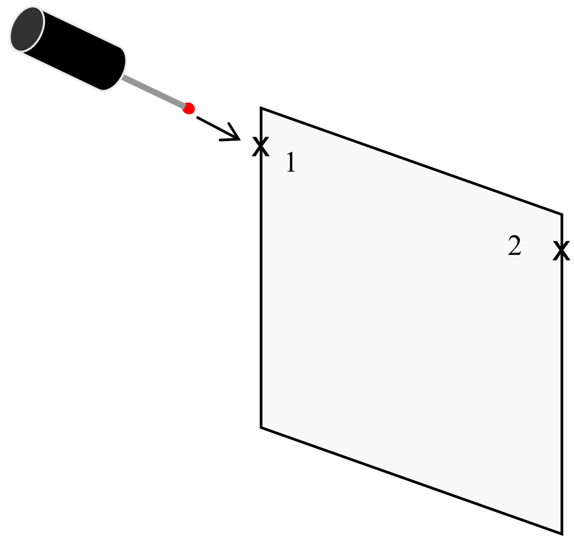

Figure 13. Illustration of the location of the side edge points measured during the manual alignment.

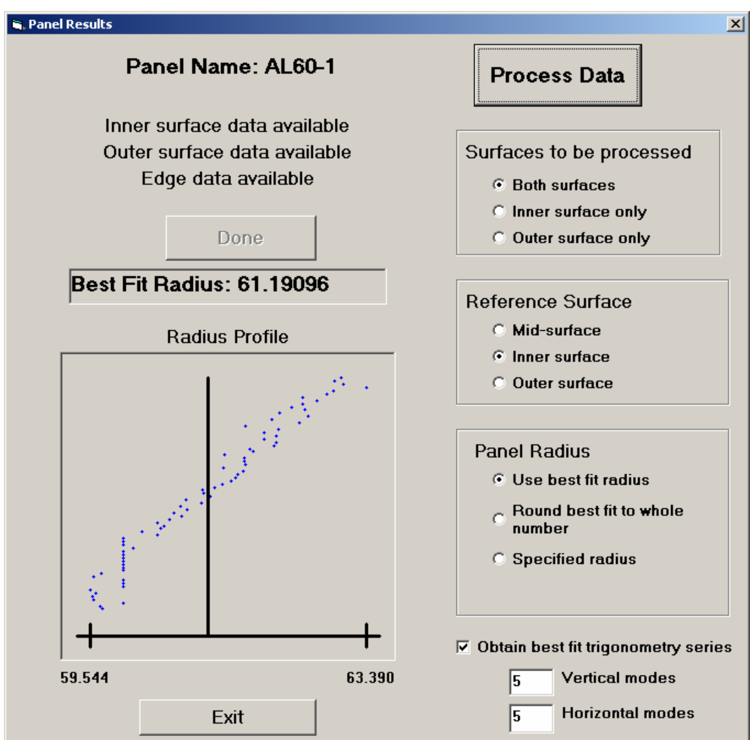

Figure 14. Panel post-processing window in MeasPanel.

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14. ABSTRACT
This paper summarizes the methodology used to measure imperfection and thickness variation for flat and curved panels using a Coordinate Measurement Machine (CMM) and the software program MeasPanel. The objective is to provide a reference document so that someone with a basic understanding of CMM operation can measure a panel with minimal training. Detailed information about both the measurement system setup and computer software is provided. Information is also provided about the format of the raw data, as well as how it is post-processed for use in finite-element analysis.

15. SUBJECT TERMS
Coordinate; Imperfection; Machine; Measurement; Panels

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