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ABSTRACT

An automated inspection system has been developed to inspect the o-ring sealing surfaces on the Space Shuttle reusable solid rocket motor (RSRM) case segment joints. A laser digitizing system is used to create a three dimensional map of the o-ring sealing surfaces. This data is analyzed for any irregularities, which are noted for further inspection and disposition. This paper describes both the hardware and the software used to gather data as well as the methods developed to analyze the data.

The RSRM is assembled from four casting segments. Each of the field joints between these segments is sealed with three o-rings. These o-rings are critical for the proper operation of the motor. After launch the booster segments are recovered and reused. As part of the refurbishment process the o-ring sealing surfaces are inspected for any irregularities. The system developed uses a combination of commercial and customized hardware and software. The system uses two computer systems in a real time environment to control a laser, an XYZ precision table, and case rotation and position information. The system is capable of inspecting both the tang end and the clevis end of the RSRM field joint. The o-ring grooves and flat sealing surfaces are inspected.

INTRODUCTION

This paper describes a unique application of a laser digitizing system. The system was created to inspect the o-ring sealing surfaces of the RSRM field joints. A combination of commercial and in-house hardware and software was used for the system. This system is known as CAJSIS (Computer Aided Joint Seal Inspection System). The data gathered by CAJSIS is used as a screening tool to identify areas for additional inspection and measurement.

After each shuttle flight the RSRMs are recovered and refurbished. Part of the refurbishment process involves inspecting and reworking the o-ring seal surfaces. Reworking involves blending any corrosion pits, scratches or anomalies to meet specification requirements.

CAJSIS measures the size and location of reworked areas. The result is a full 360° map of the sealing surfaces. The CAJSIS data is verified by hand inspection and used to assure that the reworked areas meet specifications so that the o-rings will operate properly during motor operation.

CONCLUSIONS

The CAJSIS system is a good screening tool for finding pits on the RSRM sealing surfaces. When used in conjunction with hand measurements it provides a system that is less subjective and more repeatable than hand measurements alone. CAJSIS also maintains a history of the seal surface measurements for tracking purposes.

CAJSIS saves many hours of manual labor by identifying areas for further measurement. The alternative to CAJSIS is a full manual inspection of the sealing surfaces which is time consuming and prone to error.

DISCUSSION

The discussion will first cover some background on the RSRM field joint, followed by the operation of CAJSIS and then a detailed description of the CAJSIS hardware. Finally results and error analysis will be discussed.

Background

The RSRM field joint is a tang and clevis type joint with a capture feature to reduce joint rotation (see

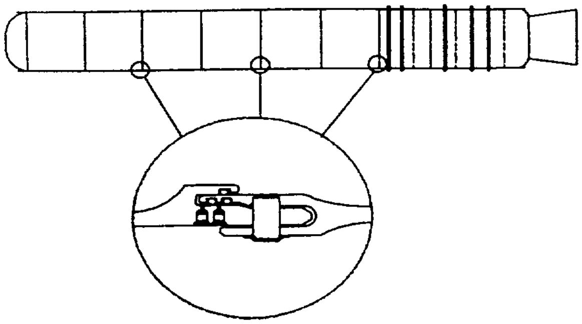

Figure 1 - RSRM Field Joints

Figure 1). Each RSRM contains three field joints. Each field joint contains three o-rings. The o-rings are known as the primary and secondary seal o-rings and the capture feature o-ring. Each of the three o-rings fits into an o-ring groove and seals against a flat seal surface. CAJSIS scans both the bottom of the o-ring groove and the flat o-ring seal surfaces.

Figure 2 is a sketch showing the scan region of the seal surfaces. The scan region axial limits are determined by finding the edges of the groove or joint tip. CAJSIS uses the laser to find the edges of the groove and scans as much of the bottom of the groove as possible. The limits for the flat seal surfaces are referenced from the clevis or tang joint tip. The joint tip location is found using the laser.

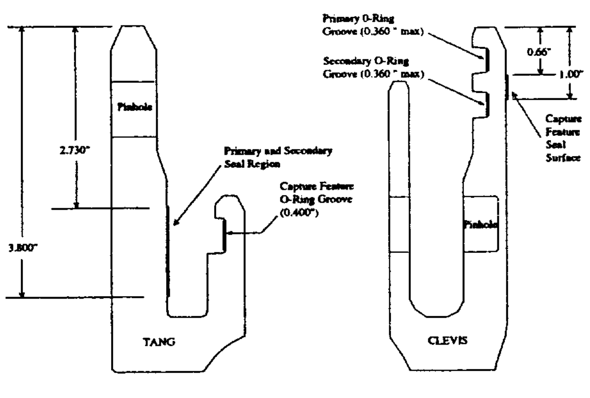

Figure 2 – CAJSIS Scan Regions

Operation

Figure 3 shows the CAJSIS system during operation.

The scanning operation begins by lowering the RSRM case segment on to a rotation table. The case sits

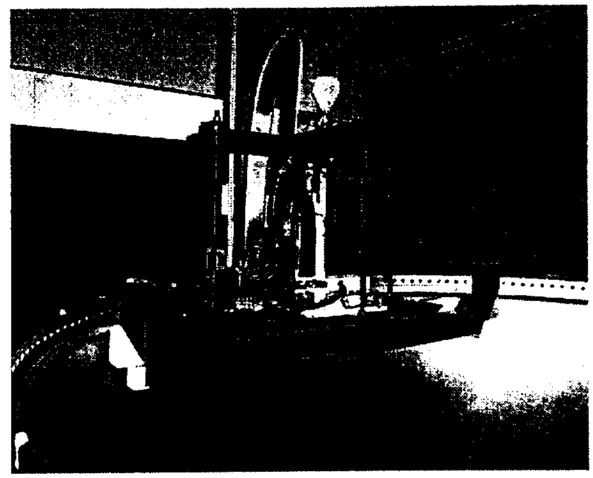

Figure 3 – CAJSIS system

vertically on the rotation table. Next the scanning system fixture is lowered on to the case segment. The end of the segment supports the system fixture. An XYZ table on the system fixture moves the laser during the scanning operation.

The XYZ table is capable of 6.0 inches of travel along each axis. However, the maximum circumferential scan length is limited due to clearance between the case and laser probe. The capture feature groove has a maximum scan length of 4.5 inches while the other scans are limited to 5.3 inches. The actual scan lengths vary depending on case rotation between scans.

A check of system operation is performed with a reference block prior to scanning each segment. After completion of the reference scan, CAJSIS determines the scan region. Depending on the surface to be scanned either the joint tip or the two groove edges are found with the laser. This information is used to define the axial limits of the scan region. A configuration file determines the circumferential limits.

The laser head moves back and forth circumferentially to complete a scan line. At the end of each scan line the laser head moves down axially and does the next scan line. The laser depth measurements take place approximately every 10 mils (0.01 inches) while the laser moves along a scan line. Scan lines are 10 mils apart. This results in a 10 by 10 mil map of the seal surface.

Once a scan is completed the case segment is rotated approximately 5 inches and the next region is scanned. Scan size varies slightly due to variability in the case rotation. Each scan overlaps the previous scan by 0.1

inches. Scanning continues in this fashion until the entire circumferential region of the sealing surface has been scanned.

A single 5 inch scan takes 4 to 15 minutes depending on the size of the area to be scanned and the surface finish of the case. Total scan times for all seal surfaces are typically 30 to 60 hours per segment. Except for initial setup the scanning is automatic and does not require operator attendance.

The output data from the laser program consists of X, Y, Z data values for each scanned point. The Laser reading is added to the z-axis value and only a total Z value is reported.

Each scan is saved in a separate file. The scan data is analyzed with a separate filtering program. The filter program calculates the angular location, length, width and depth of each pit. This data is printed and used for hand inspections.

Hardware

The Major CAJSIS hardware components and their functions are:

- Laser System
  - Laser computer – Controls laser and XYZ table.
  - XYZ table – Positions laser relative to case.
  - Laser – performs surface measurements.
- Control computer – controls rotation table, pinhole camera and safety features. Performs data analysis and storage.
- Case segment rotation table.
- Pinhole camera – determines angular location.
- Safety systems – Light curtain, manual emergency stops, breakaway feature.

Laser System

The laser system includes the XYZ scan table, laser power source, computer interface boards and software and a laser sensor. A Compaq 60 MHz Pentium computer controls the laser system. The laser computer and power supply are located in the CAJSIS control room. The rest of the laser system is located on the system fixture.

The system fixture (Figure 4) holds the XYZ table, lasers and pinhole camera. The purpose of the fixture is to provide a stable platform for scanning while allowing the case to be rotated. The main components of the system fixture are a large aluminum base and an attach system which holds the system fixture on the joint. The system fixture is lowered onto the segment with a cable and winch assembly. Four rollers resting on the segment joint tip support the fixture. Four pneumatic pressure rollers clamp on to the sides of the case to hold the fixture securely. The complete assembly is attached to the main facility beam by a pneumatically activated ball and clamp fixture.

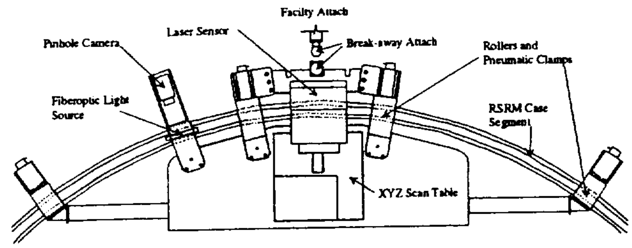

Figure 4 - CAJSIS System Fixture

The laser XYZ scan table (Figure 5) is an accurate positioning device driven by servomotors. Glass scale encoders measure the positional location. Each of the 3 axes has an accuracy of 0.1 mils (0.0001 inch), with a combined accuracy of approximately 0.5 mils. The XYZ table has 6 inches of travel along each of the axis. The X-axis is oriented in the circumferential direction of the case. The Y-axis is axial and the Z-axis is radial.

The laser head was custom built for the CAJSIS application. The laser beam in the CAJSIS sensor is reflected 90 degrees from the source so that the laser head can fit within the confines of the field joints (Figure 6). The laser sensor is a solid state gallium-arsenide (GaAs) pulsed laser with peak power output of 0.6mW at a wavelength of 780 nm.

The laser beam is reflected from the seal surface onto a CCD (Charge Coupled Device) array. The location of

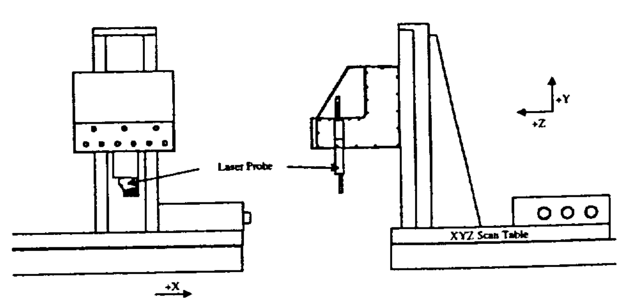

Figure 5 - XYZ Scan Table

the beam on the CCD array is converted into a distance using triangulation. This distance is added to the z position from the XYZ table, yielding a Z position measurement. The software adjusts the Z-axis of the XYZ table to keep the laser focused in the center of its range.

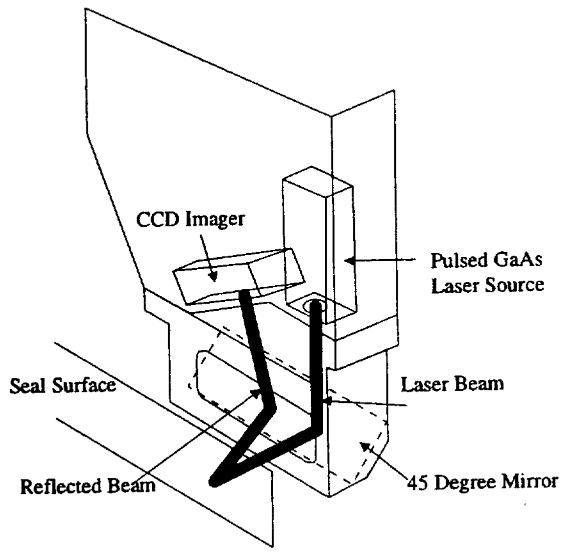

Figure 6 - CAJSIS Laser Probe Design

The CAJSIS system uses one of two lasers depending on the surface being scanned. A long standoff laser was designed to scan the o-ring grooves. It has a standoff distance of 0.25 inches, slightly greater than the depth of the o-ring grooves. This laser is used for the two clevis grooves and the tang groove. A second short standoff laser is required to scan the tang seal surface. This laser was required because of the tight clearance between the tang seal surface and the capture feature. The short standoff laser has a standoff distance of 0.17 inches. Either laser can be used for the clevis capture feature seal surface. Both lasers have a range of 0.024 inches. The CCD contains 256 elements giving the laser a theoretical accuracy of 0.1 mils.

Rotation Table

The function of the CAJSIS rotation table is to rotate the RSRM segment in 5 inch increments so that the next scan can be performed. Rotation of the segment is performed after each scan. Rotation is controlled by the control computer and measured by the pinhole camera.

Pinhole Camera

The RSRM joints contain 180 pinholes. These pinholes are used by the CAJSIS system to keep track of the angular location of the case segment as it rotates. The pinhole system consists of a CCD camera located on the system fixture outside of the case and a fiber optic light source located inside the joint. The pinhole camera optically determines the location of the pinhole edges. The field of view of the pinhole camera is a little more than 2 degrees, so two pin hole edges are always visible. The software converts the edge information into an angular location. The operator sets the initial angular location, and then the software keeps track of the angular location by counting the number of holes and the position of the pinhole edges. The angular location is measured to one hundredth of a degree. The required accuracy is 0.5 degrees.

Control Computer

A Silicon Graphics (SGI) computer controls the overall operation of the CAJSIS system. The system provides the user interface, directs the laser computer, rotates the case, calculates angular location, stores the data and analyses the results.

When the system was designed in 1992 it was necessary to split the scanning job between the two computers. Today it would be possible to run the system with one computer. However, this would require a redesign of the system and a substantial rewrite of the software.

The control software was written in-house. Two programs operate in real time mode to watch the safety systems and the pinhole camera. Additional software sends commands to the laser computer and controls the case rotation. All user interaction is done from the control computer. Programs on the control computer also analyze the data and provide graphical and printed output. Remote monitoring of the scan progress and summary output for all scans is available via an intranet web page served by the control computer.

Safety Systems

Several safety systems have been implemented for the protection of personal and the RSRM hardware. Light curtains shut down the system if anyone approaches the system fixture. This prevents any exposure to the laser or the possibility of sticking a finger between the case and rollers. Manual emergency stop buttons at several locations stop the case rotation, XYZ table movement and shutdown the laser.

Protection of the RSRM hardware from damage is assured by two systems. Contact of the laser head with the segment or any other component will stop scan table movement. The other safety feature is the system fixture attach. A severely out of round case will bind against the system fixture as the case rotates. If this happens the system fixture breaks away from the attach point and sends a signal to stop the case rotation.

<u>Data Analysis</u>

The data analysis software calculates the size, shape and depth of a pit. Pits are defined as material missing from the unaffected surface. The challenge is to define the unaffected surface. The software algorithm curve fits the measured data to estimate the unaffected surface. This surface is subtracted from the measured surface to obtain the pit measurements.

The first step is to calculate the local curvature of the case. The raw data is curve fit using a non-biased least squares curve fit.[1] Pits or noise in the data affect the curve fit, therefore points which are furthest from the curve fit are removed and the data is refitted. This is done three times. Each scan line of a 5 inch scan is curve fit separately. This avoids the effects of the system fixture not being perfectly perpendicular to the scan surface plane.

The raw scan data for one scan line and the final curve fit is shown in Figure 7. The elliptical arc appearance of the data is a plotting artifact due to the different scales on the X and Y axes. This particular scan line covers 5.15 inches and contains 532 points. This scan was determined to have a 4.9 mil pit that can be seen near the center of the plot.

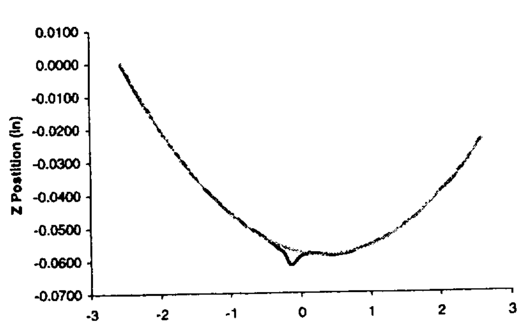

Figure 7 – Raw scan line data and least squares circular curve fit.

Experience shows that pits near the center of the plot are measured accurately, while pits near the edge of the scan are underestimated by 0.5 to 1.0 mils. Areas with a great number of pits also tend to be more difficult to filter and can be underestimated by 1.0 to 2.0 mils. Estimation of the unaffected surface is the key to the filtering process.

Once the curve fit has been found it is subtracted from the raw data. Figure 8 shows the results from this subtraction applied to the data in figure 7. This procedure is applied to each of the scan lines. The resulting data is searched for points that exceed the pit threshold, defined as one mil. Once a pit has been found the edges of the pit are followed to determine the size of the pit. The software calculates the depth, width, height and angular location of each pit. The pits are then sorted by angular location and printed out.

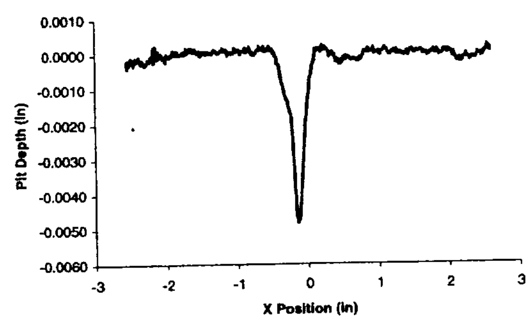

Figure 8 – Filtered Scan Line Data.

The data for each scan is stored in a database that is accessible on a local web server. Figure 9 shows a typical data plot from the web server. This plot shows the pit depth versus the angular location. The case segment shown has been scanned twice. The previous scan data is plotted along with the current data.

Error Analysis

The accuracy of the system is affected by both hardware and software. On the hardware side, both the laser and XYZ table report measurements to 0.1mils. The error will be greater than this. Unfortunately the only independent data that could give any insight to the

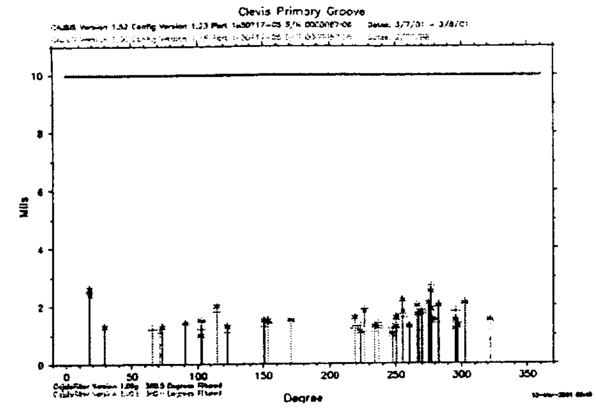

Figure 9 – Pit depths and locations for 2 scans of the same case segment

error is a limited set of hand measurements. The hand measurement data is only reported to the nearest mil.

Starting in 1997 hand measurements have been taken for all the pits deeper than a defined limit with a minimum 8 measurements on each seal surface. CAJSIS is used to identify which pits to measure. The hand measurements are made using various tools depending on the seal surface to be measured. What they all have in common is that the operator must compare a measurement of the pit to a measurement of an unaffected area. As with CAJSIS the determination of the unaffected area is difficult at times.

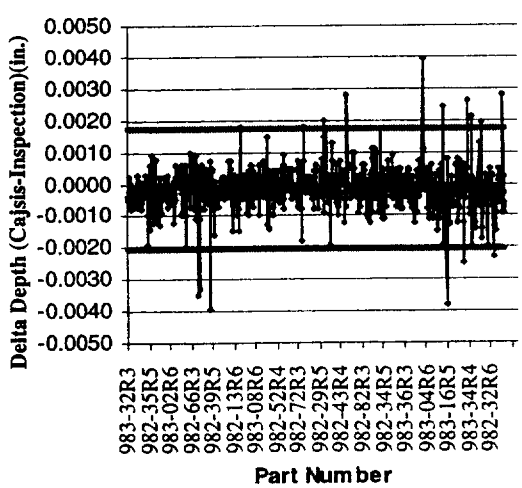

Figure 10 – Comparison of CAJSIS data and hand measurements.

Figure 10 shows the difference between CAJSIS and hand measurements over a series of 104 segments for the tang seal surface. Negative numbers mean that the hand measurement was deeper than the CAJSIS measurement.

There are six pits shown in figure 10 where the hand measurement is more than 2 mils deeper than the CAJSIS measurement. Four of these pits are axially on the lower edge of the scan region and the maximum depth was not within the scan region. CAJSIS reported the maximum depth within the scan region. The other two pits are underreported by CAJSIS due to the presence of another deeper pit at the end of the scan lines.

The average hand measurement is 0.2 mils deeper than the CAJSIS measurements. This may simply be due to hand measurements being reported to the nearest mil.

The 3-sigma standard deviation of the difference between the hand and CAJSIS measurements is 1.9 mils. It is difficult to attribute the error to either measurement since there is some uncertainty in both the CAJSIS measurement and the hand measurements. Hand measurements have been repeated on a small subset of the data, this shows the variability of hand measurements to be slightly greater than the CAJSIS variability. Attributing all of the variability to CAJSIS gives a 3-sigma measurement variation of 1.9 mils, while assuming CAJSIS and hand measurements have equal variability results in a 3-sigma measurement variation of 1.3 mils.

The measurement variation for CAJSIS is similar or better than hand measurement variation. However, there are significant outliers in the CAJSIS data. In all instances examined, these outliers were the result of CAJSIS overestimating pit depth in regions having multiple pits. Since CAJSIS is used as a screening tool for further measurements this is acceptable.

Changes in the filtering techniques may improve pit measurement accuracy in densely packed areas. However, these techniques are still under development and have not yet been implemented on the production system.

References

1. Joseph, S. H. "Unbiased Least Squares Fitting of Circular Arcs", Computer Vision Graphics Image Processing 56, September 1994, p424-432.