AUTOMATED OUTER MOLD LINE (OML) MEASUREMENT AND CONTROL

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ABSTRACT

Stringent step and gap tolerance requirements are placed upon outer mold line components such as fixed skins, panels and doors. The aircraft design identifies these steps and gaps as key characteristics which must be measured and controlled. The current processes for achieving these requirements are manual, non-robust and require several iterations of measurements to achieve the desired results – all which add to the product cost and cycle time.

To address this need, Northrop Grumman Aerospace Systems (NGAS) Manufacturing Technology Development organization is developing OML measurement and control system utilizing state-of-the-art metrology technologies.

One of the systems tested for this application was the Laser Radar (LR) method in which data was compared with standard calibrated blocks to determine accuracy of the measurements.

A test mock-up was created to simulate the gap and step condition encountered during the skin/panel assembly. Measurements were made using the LR method along edges and knowing the thickness and cavity depth condition, shim size calculation was computed.

On the aircraft assembly, the system will be designed to predict the shim size and location to achieve OML control based upon composite part thickness and "as built" location of the underlying structure while providing assembly guidance to the mechanics regarding size and location of the shims. The ultimate goal is to implement a robust automated measurement system that meets required measurement accuracy, is affordable, and provides a "value-approach."

Data and analysis so far indicate that LR method may be effective for skin and panel measurements, depending upon measurement accuracy requirements. For composite part thickness measurements, however, additional development work may be required.

The paper covers current measurement processes, tight measurement accuracy requirements, LR system, lab test plans, methodology, results and conclusions, as well as concepts for automated OML measurements.

STEP & GAP DEFINITION

Outer Mold line (OML) has two components: Step and Gap. Step measurement is defined as a vertical distance between the two adjacent planes measured at the center line of the gap, as shown in Figure 1 below. Gap is simply defined as horizontal distance between the two adjacent OML surfaces.

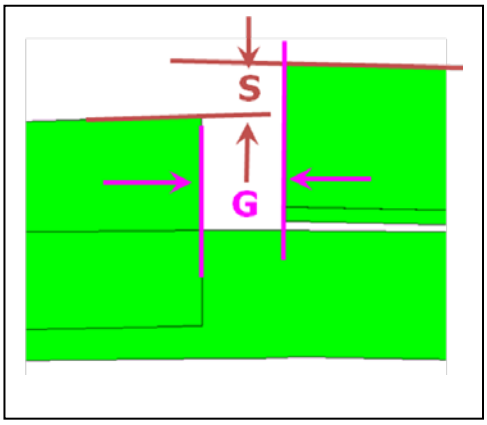

Figure 1. Step and Gap Definition

In reality, two adjacent surface edges may have imperfections (e.g. caused by paint, edge roughness, etc), that may distort the step measurement. In order to minimize this distortion, the following approach may be used to compute the step height.

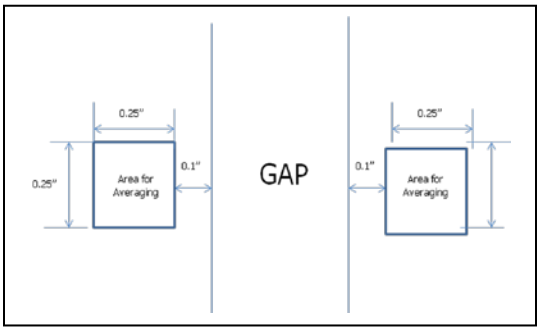

Figure 2. Measurement Patches for Step Calculation

Small measurement patches 0.25"x0.25" may be created about 0.1" away from each edge. (Figure 2). Planes are then fitted over these patches and extended over the middle of the gap to determine the step amount. In this case, vertical distance between the two extended planes in the middle of the gap is the step amount.

PROBLEM STATEMENT AND HYPOTHESIS

Outer mold line of the aircraft has a step and gap requirement that must be met for design and maintainability reasons. Typical call outs for step requirements can be as tight as +/- 0.007”, while the gap requirements can vary with a minimum of 0.190” to a maximum of 0.350”, depending on aircraft OML surface area. The + or - sign in front of the tolerance call out indicates relative position of the adjacent OML surface.

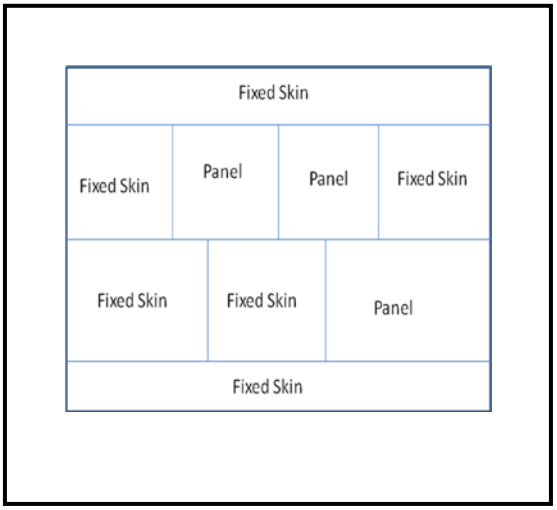

Figure 3. Skin/Panel Layout - Notional View

Between the gap and step requirement, step requirement is much harder to achieve. Therefore, in this paper we will focus on step measurement requirements. Figure 3 above shows a notional representation of the skin and panel configuration on the aircraft OML surfaces

Wherever fixed skin mates with another fixed skin or the panel, there is requirement to meet both step and gap tolerances. Assuming there are, on the average, 40 points to measure, and about 20 skins and panels per aircraft, there could be as many as 800 points for which step and gap conditions requiring measurement. An example of skin measurement plan is shown in Figure 4 below.

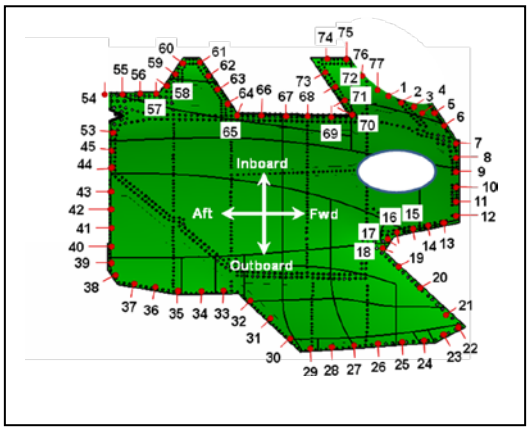

Figure 4. Fixed Skin Measurement Plan

Available measurement tools for step and gap condition range from mechanical type, such as depth gauge or Tru-Lok gauge, to hand held laser measurement devices such as Gap Gun or Laser Gauge (Figure 5). These laser devices have a laser beam that is projected on the OML surface and the image is captured on a camera for taking step and gap measurements.

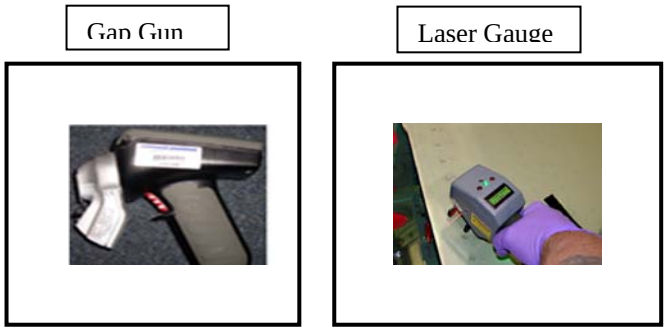

Figure 5. Gap Gun and Laser Gauge

CURRENT MEASUREMENT PROCESS

The skin and panel assembly process begins with dry fitting of the skin using pilot holes drilled in the skin and the structure. Fixed skins are temporarily attached to the structure and the measurements are taken with any of the devices mentioned above. Recording of shim requirements is done on a sheet of paper or hand written on a tape applied to the structure. Shim buttons are applied at hole locations to bring adjacent OML surfaces into tolerance requirement. Since the measurement process is not robust, shim size and location determination is repetitive, labor intensive, ergonomically unsuitable, and adds significant amount of product cycle time

Further, continuous improvement efforts are almost impossible to achieve as the OML data is not electronically available for Statistical Process Control (SPC) analysis.

The basic hypothesis is that metrology software and hardware technology has advanced to the point that it can be leveraged to automate the OML measurement and control process.

PROJECT OBJECTIVES

Northrop Grumman Aerospace Systems (NGAS) is evaluating different technologies available for measuring and achieving OML requirements. Several technology options are being reviewed. One of the options is a Laser Radar (LR) method for its applicability in the aircraft production.

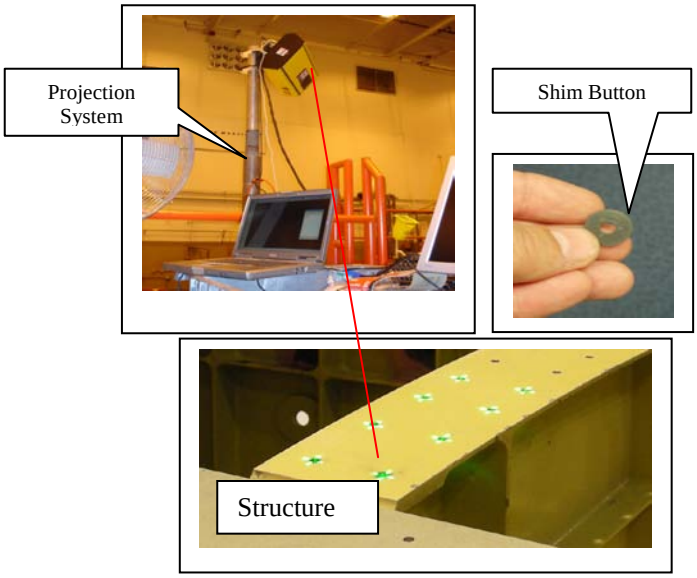

Figure 6. Shim Size and Location Projection

Significant improvements in both labor and product cycle time are expected by automating the measurement, control and reporting process. The three major areas of automation opportunities are:

1. Composite part thickness measurement
2. Skin/Panel assembly system which measures OML features and "as-built" structure
3. Automatic projection of shim size and location based upon part thickness and "as-built" structure condition (Figure 6).

LR TESTING APPROACH

The testing and evaluation of the system was conducted using standard calibrated blocks, and on a specially designed simulated test fixture.

LR SYSTEM

System Hardware (Figure 7):

The Nikon's (formerly Metris) LR system consists of a measurement head mounted on gimbals that provides 360 degrees rotation. For improving measurement coverage, it can be securely mounted on a tall Brunson stand. The measurement unit is connected to the system controller, which directs head motions, compile collected data and present the user information in an easy to understand format.

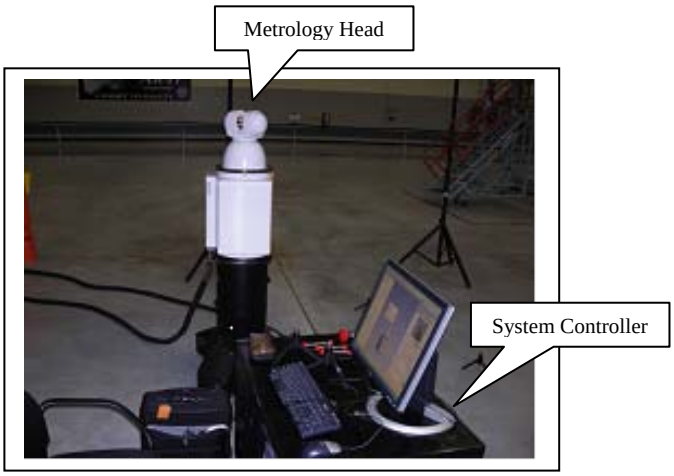

Figure 7. Laser Radar (LR) System

The rationale for the selection was:

- It provides automated non-contact measurement capability for large volume application up to 60 meters
- Rapid data collection up to 1000 points/second without photogrammetric targets

- It has a published 3D accuracy (2Sigma): 16 microns (0.00064”) at 1 meter and 240 microns (0.0096”) at 24 meters.

Interface Software:

Verisurf software was selected due to its easy interfacing capability with the LR system. Computer Aided Design (CAD) models of the skin and the structure were imported into the system software. A specially written program then directed the LR metrology head to measure the OML points, acquire the data, provide deviation analysis and create inspection reports.

SHIMMING COMPUTATION ALGORITHM

To bring adjacent skins and panels to meet the tolerance requirements, calculated shims are placed around edges on the mounting holes of the fixed skins. The number of measurement points selected for each skin can be as many as 20% of the total number of skin attach holes. Since the panels are Interchangeable and Replaceable (I&R), it is the fixed skin edge holes that get the shim to bring skin/panel interface into OML tolerance.

There are a number of ways to compute shim thickness, depending upon selected shim computation method.

One method for shim thickness selection is described below:

When a fixed skin meets another fixed skin, relative step measurements between the two surfaces are made. Shim size and location are determined to bring the two surfaces in step tolerance. For a case where the skin and panel meet, cavity height constant values may be predetermined by engineering and documented on the skin/panel assembly drawings. Shim size is computed by the following formula:

Shim size = Cavity height constant – “as built” cavity depth- thickness of the skin

Therefore, to achieve OML, the following measurements are required:

1. Thickness of the part around the edges
2. Relative step between the fixed skins
3. As-built cavity depth where panels are fitted

MEASUREMENT ACCURACY REQUIREMENTS

For our tests, these requirements were detailed in the testing documents. To summarize they are shown in Table 1 below:

Table 1, Measurement Accuracy Requirements

Feature	Tolerance	Accuracy
Step	+/-0.007"	+/-0.001"
Gap	+/-0.007"	+/-0.001"
Part thickness	+/-0.005"	+/-0.001"

Required process capability of the system can be as high as 3 Sigma. This means that 99.7% of the time the measured reading will be between +/-0.001".

LR System Test

To compare the LR measurement accuracy, standard calibrated blocks in 2.0” 3.0” and 4" lengths were used. The radar beam was directed on the front face of the block and the reference plane from approximately 15' (Figure 8).

Table 2, Deviation from Calibrated Blocks

Block Length	LR	Deviation
2.0000"	2.0023"	0.0023"
2.0000"	2.0019"	0.0019"
2.0000"	2.0021"	0.0021"
2.0000"	2.0006"	0.0006"
3.0000"	3.0018"	0.0018"
3.0000"	3.0032"	0.0032"
3.0000"	3.0026"	0.0026"
3.0000"	3.0024"	0.0024"
3.0000"	3.0030"	0.0030"
4.0000"	4.0015"	0.0015"
4.0000"	4.0010"	0.0010"
4.0000"	4.0011"	0.0011"
4.0000"	4.0021"	0.0021""

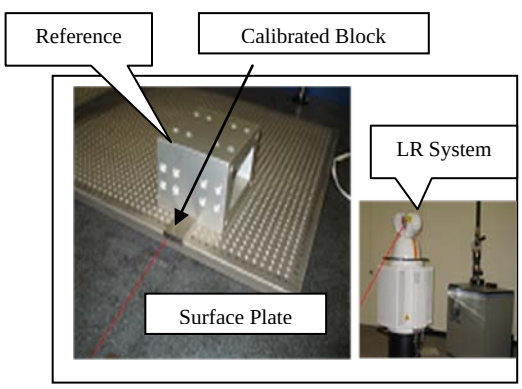

Figure 8. Measurement of Calibrated Block

The deviation between LR and the standard block measurement ranged from 0.0006" to 0.0032" (Table 2). Figures 9 shows LR deviation and Figure 10 shows the histogram

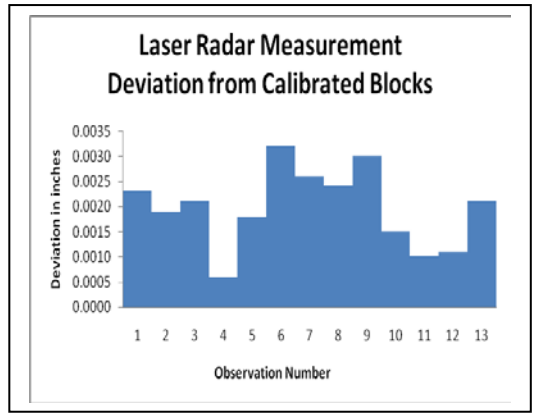

Figure 9. LR Deviation from Calibrated Blocks

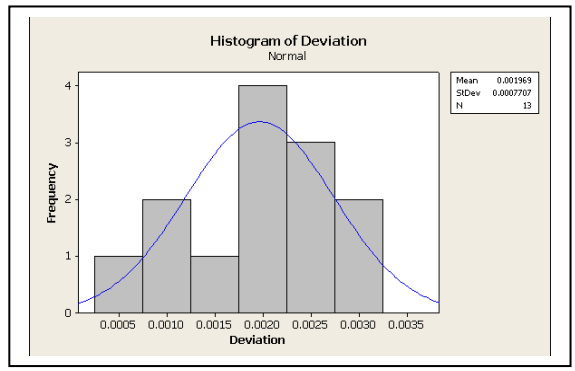

Figure 10. Histogram Thickness Deviation

Mean thickness = 0.001969", Standard deviation = 0.00077"

Simulated Test Article

A simulated test article was fabricated to test the software, validate the performance and usability of the Human Machine Interface (HMI). The test article consists of three pieces - a constant thickness skin with full size hole pattern, a metallic base which represents air frame with full size hole pattern and different thickness shim buttons for driving the skin to OML. This was accomplished by creating a CAD model that represents a skin with constant thickness and a replication of air frame with exaggerated

step condition (Figures 11 & 12). The CAD model was sent to be N/C machined out of aluminum to a tolerance of +/-0.0025" and CMM inspected to verify machining accuracy.

The base was machined with a slight curvature and varying cavity depths around its periphery to represent aircraft mold line. The constant thickness skin, when assembled in the base with proper calculated shims, would achieve a nominal (0.000”) OML

Skin Thickness Measurement:

An automated set of 11 points were selected on the OML side of the skin. The first set of measurements automatically created vectors that are needed for thickness calculations. The skin was turned around and the second set of points was taken on the exact vector lines created from the first measurements. Skin thickness at these points were calculated by the distance between the two points

OML Measurements:

Step measurements were taken to determine the depth of the cavity where OML skin will fit. Cavity depth was taken by the LR by fitting into the simulation tool reference system using the CAD model.

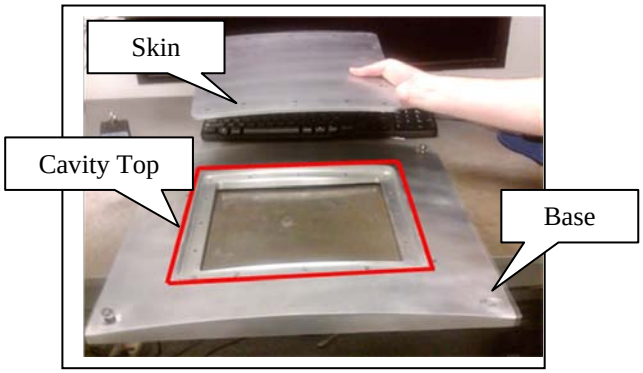

Figure 11. Cavity Top Measurement Locations

An automated set of 11 points were taken on the OML of the upper part of the step of the simulated air frame tool. Another automated set of 11 points were taken in front of but offset to the first set. Cavity depth was calculated by the distance between the intersection points of the first and second measurements.

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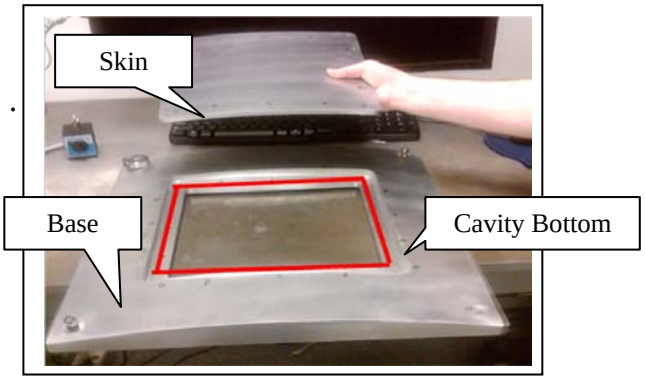

Figure 12. Cavity Bottom Measurement Locations

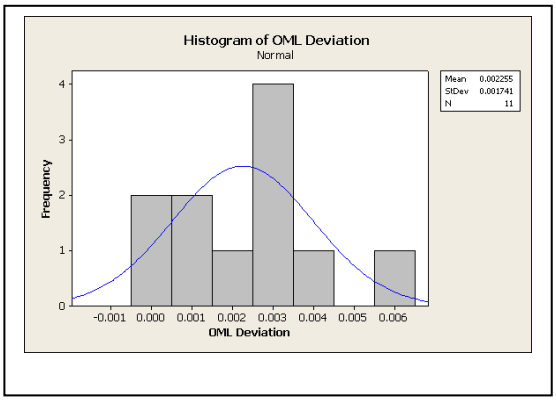

Figure 13. Histogram of Deviations

The shim thickness was calculated as: Shim thickness = Cavity depth - Skin thickness

After the computed shims were placed between the base and the skin in the cavity, the base and skins were assembled and the OML between the base and the skin was measured.

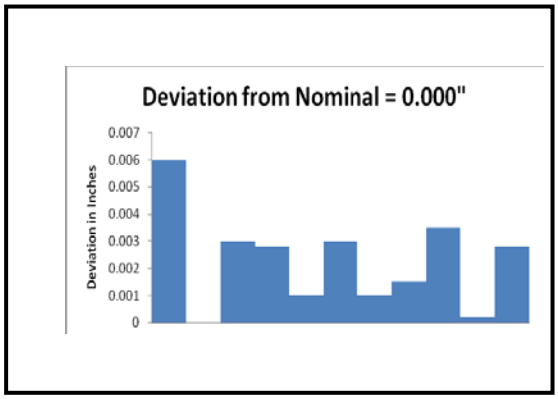

Figure 14. Deviation from Nominal

The deviation from nominal value is shown in Table 3.

Table 3, OML Deviation from Nominal = 0.000"

Point	Skin	Base	Deviation
1	0.001"	-0.005"	0.006"
2	0.003"	0.003"	0.000"
3	-0.003"	0.000"	0.003"
4	-0.001"	0.0018"	0.0028"
5	0.001"	0.002"	0.001"
6	-0.002	0.001"	0.003"
7	0.004"	0.003"	0.001"
8	0.001"	0.0025”	0.0015”
9	-0.0025	0.0010”	0.0035”
10	0.0020	0.0018”	0.0002”
11	0.0018	-0.001”	0.0028”

Figures 13 and 14 graphically show the OML deviation data.

Mean deviation: 0.0023”

Standard deviation: 0.0017

Automated Part Thickness Measurement

For automating part thickness measurement using LR, one could consider the following process:

1. Attach four tooling balls to the skin to create a reference plane
2. Auto measure with LR measurement points per plan (Figure 15)
3. Create and project normal vector on the other side from the same point

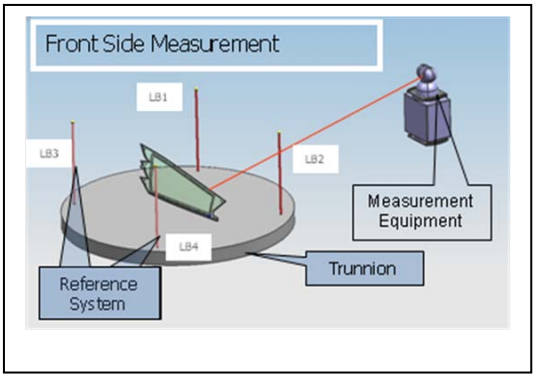

Figure 15, LR Measurement - Front Side

4. Turn the part around (Figure 16)
5. Measure tooling balls and realign to the same reference plane
6. Measure same points where normal vector was earlier projected
7. Compute thickness from the distance between the two points

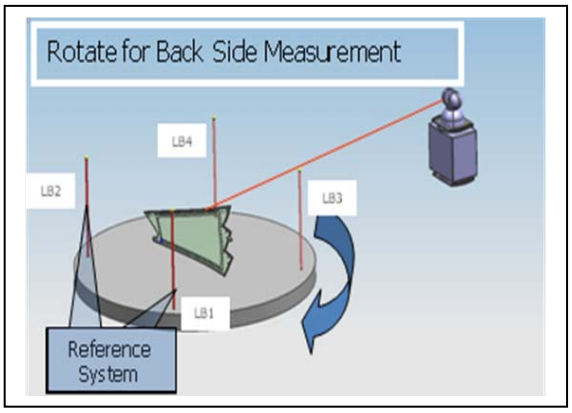

Figure 16, LR Measurement - Back Side

Automated OML Measurements (Figure 17)

The following concept is presented for automation of OML measurements using LR

1. Elevate LR for a clear view of the structure
2. Create LR reference plane using tooling balls that may be available in the work stand
3. Write an automated measurement plan for LR to take measurements at the designated points
4. Dry fit skin and cleco it to the structure
5. Take OML measurements using the existing method
6. Measure OML using LR measurements of at the same locations
7. Compare measurement data between LR and existing method for verification

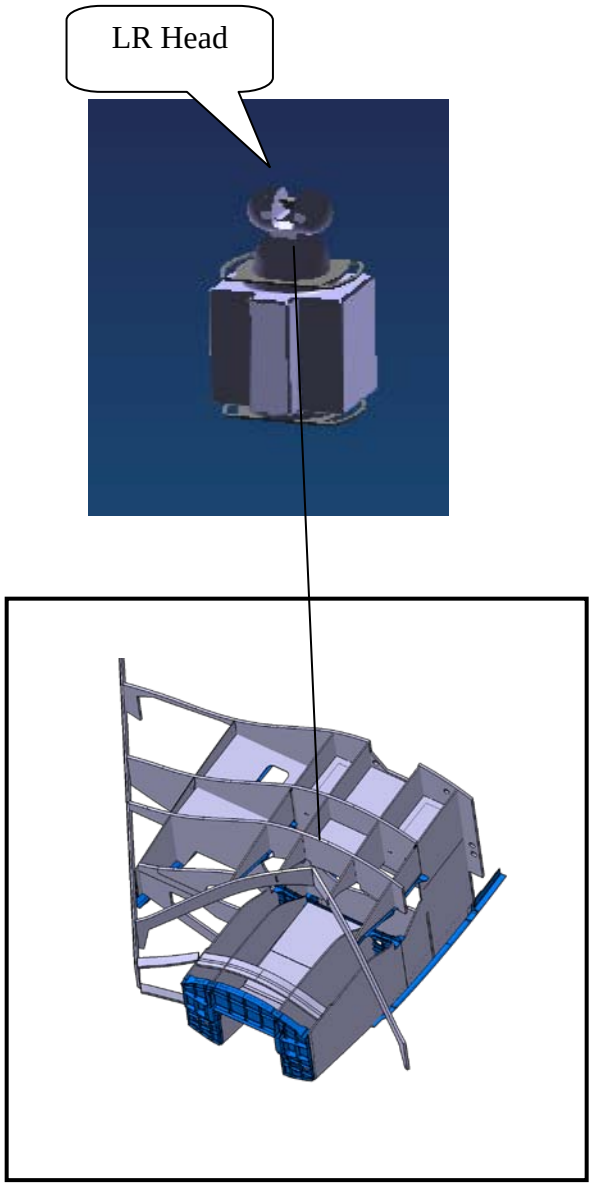

Figure 17. Automated OML Using LR

CONCLUSIONS

LR may be used as a non-contact method for automating OML measurement process. Once the interface program is written according to the measurement plan, it can sequence itself for automated measurements.

The most important requirement of the measurement system is its capability to provide accurate measurements consistently. The next factor is affordability, meaning the capital invested can sustain a reasonable rate of return on the investment made.

Locating LR so that it can cover the entire aircraft's measurement range can be a challenging task. It is a lot easier to perform upper mold line measurements for top skins, panels and structure than it is to measure lower mold line skins, panels and structure. There are creative ways available to surmount this difficulty. One way is to have LR beam bounced off a mirror surface to overcome the line of sight issue. Accuracy of such method may require further investigation.

For automating measurement sequencing, LR needs to be directed to go to specific points from the CAD drawing of the skin. To do that, one might need an interface software package. Several packages are available such as Verisurf, Spatial Analyzer (SA), and PolyWorks etc., to name a few. With any of these software packages, some level of customization will be required to meet the user's specific measurement requirements.

Mean value of LR measurement of standard calibrated block varied by about 0.002" at an approximate distance of 15'.

In the simulated test, we were able to get OML mean accuracy of 0.0023" at an approximate distance of 20',

Additional testing may be required for thickness measurement of the composite parts. Higher variability in the thickness measurement is anticipated due to factors, such as paint on the part and composite material composition.

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