Laser Profilometry For Non-Contact Automated Countersink Diameter Measurement

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ABSTRACT

Automated countersink measurement methods which require contact with the workpiece are susceptible to a loss of accuracy due to cutting debris and lube build-up. This paper demonstrates a non-contact method for countersink diameter measurement on CFRP which eliminates the need for periodic cleaning. Holes are scanned in process using a laser profilometer. Coordinates for points along the countersink edge are processed with a unique filtering algorithm providing a highly repeatable estimate for major and minor diameter.

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INTRODUCTION

Mechanical hole-probing is susceptible to lube and debris buildup. This can manifest itself as a gradual degradation in accuracy necessitating frequent cleaning by machine operators. Manual methods like the check-bolt and height gauge are time consuming. Lube and debris must be removed from the hole prior to measurement to obtain an accurate result.

Electroimpact has integrated a laser profilometer into a machine tool for non-contact automated scanning of countersink geometry. The goal is to provide an efficient, accurate, and automatic measurement technique which solves the inherent problems associated with the current state of the art. The noise level and quantization error of the profilometer necessitates filtering and post processing specific to countersink measurement in order to provide accuracy and repeatability which meets or exceeds current technologies.

This paper is meant to be an initial document outlining the design of the system and providing experimental results for carbon fiber countersinks. Future research is planned as a follow up. This will include performance data from a production environment as well as feasibility for use on other materials such as aluminum.

HARDWARE

The hardware required to implement this measurement technique includes a profilometer head which houses the laser and detector, a stand-alone controller, and a PC application for post-processing. The head is mounted to the headstone of the machine tool as shown in Figure 1. Scan motion is then achieved using existing CNC-driven positioning.
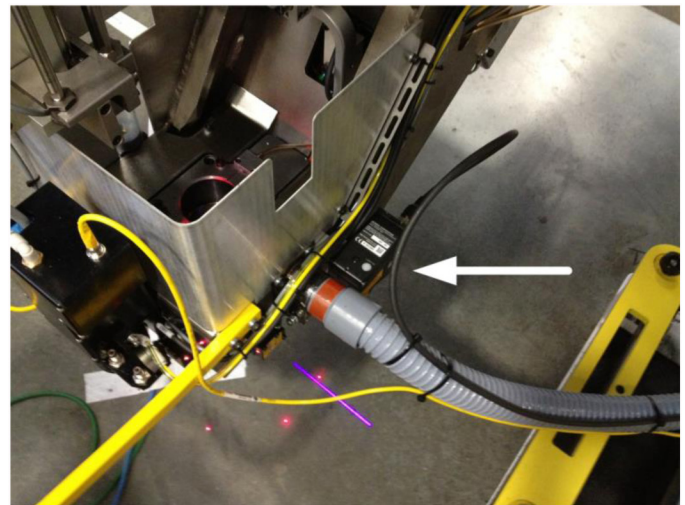

Figure 1. Mounted laser head.

The coordinate system used throughout this paper is based on the profilometer head, as shown in Figure 2. The Z-axis is aligned with the laser, positive from workpiece to emitter. The X-axis is the direction of scanning, normal to the laser profile. The Y-axis is aligned with the laser profile.

The laser profilometer provides a cross-section of the countersink by determining Z position data across the profile at quantized Y positions. As an example, typical profile data for the center of a countersink is shown in Figure 3.
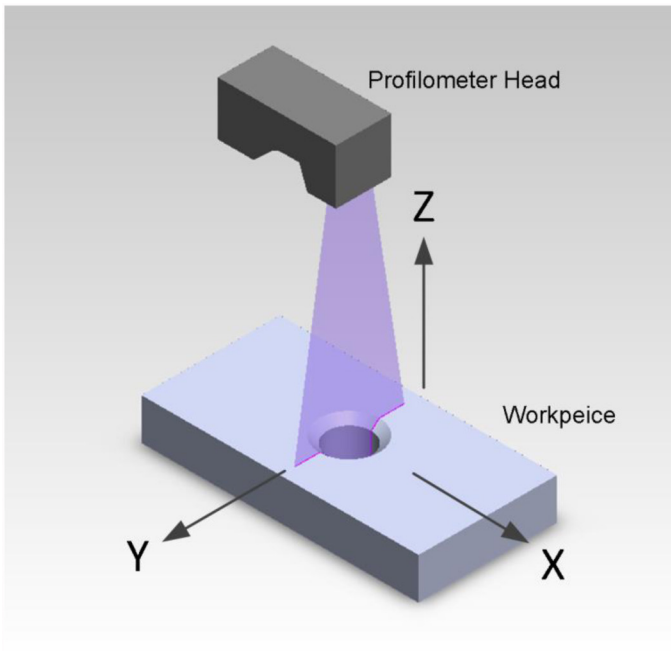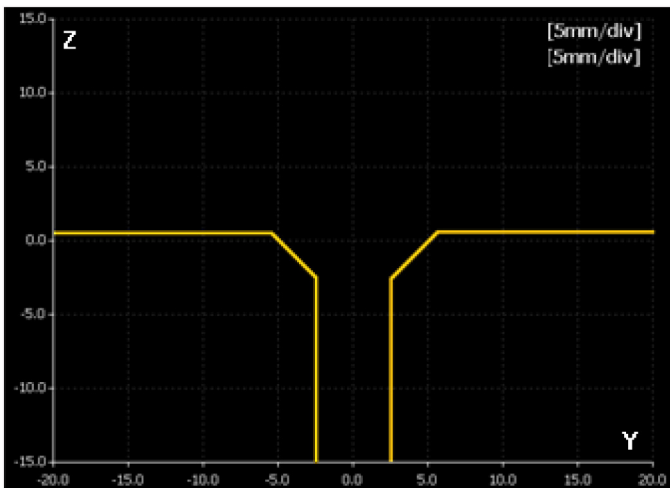
Figure 2. Coordinate system.

Figure 3. Countersink profile with scan position near the center of the hole.

The laser is driven across the entire countersink along the X-axis at a specified feed rate using the CNC. The Y position of the edge is sampled at a specified frequency using a stand-alone laser controller. For each sample, the X position is inferred from the feed rate and sampling frequency. The resulting data set is then fed into an ellipse fitting algorithm to provide major and minor diameter. A separate PC application runs this fitting algorithm as a post-processing step along with an outlier filtering routine. A block diagram showing the flow of data is shown in Figure 4.
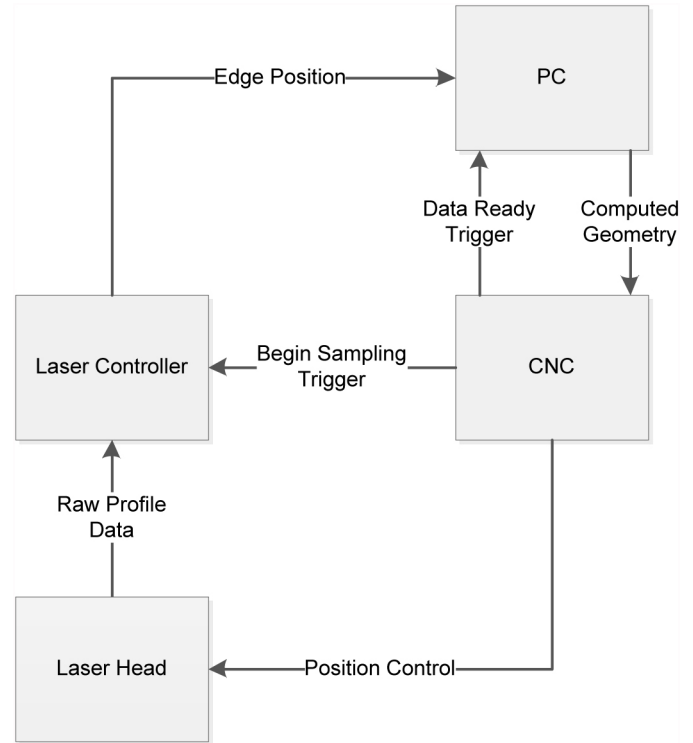

Figure 4. System diagram.

SOFTWARE

Raw Data Acquisition

It is important to note that the repeatability of the profilometer along the Z-axis is an order of magnitude better than the Y-axis. Therefore, it is advantageous to use as much Z-axis data as possible in determining edge position. To achieve this, edge location is found using the intersection between best fit lines for the inside surface of the countersink and the outside surface of the workpiece, as shown in Figure 5. This method provides a precision estimate of the Y location of the two edges visible in each profile or "slice" along the scan.
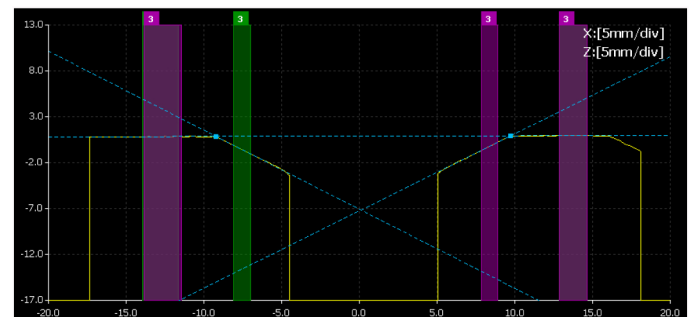

Figure 5. Edge location using the intersection of best fit lines generated within the green and purple bands.

Ellipse Fitting

Raw data is transferred to the post-processing application as a list of Y positions representing the located countersink edges for each profile. The X position is inferred for each profile using the following equation, where n is the sample index, v_x is the scan velocity, and f_s is the sampling frequency:

$$Y = n \frac{v_x}{f_s}$$

(1)

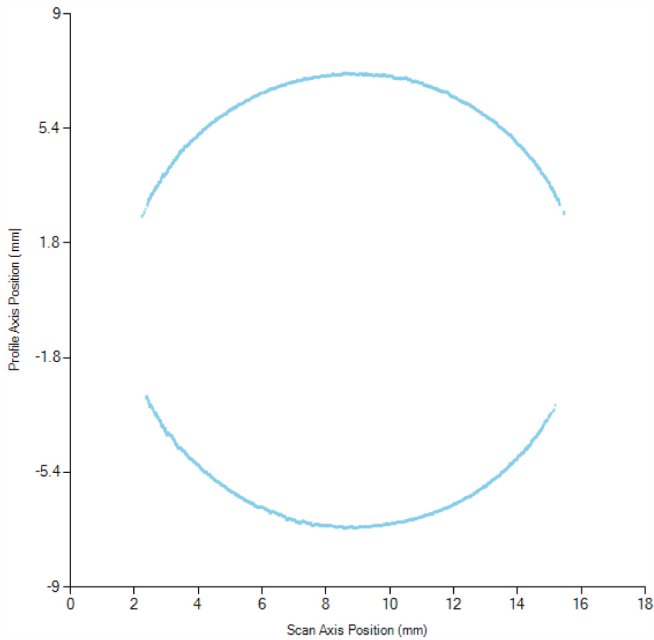A typical set of X and Y edge position data is shown in Figure 6.

Figure 6. Raw Y data plotted against X position inferred from scan feedrate and sampling frequency.

For some applications, a best fit circle would provide a sufficiently accurate estimate for countersink diameter. However, many factors induce eccentricity in the countersink (i.e. normality of the cutter relative to the workpiece surface, curvature of the workpiece surface, reaming/countersinking of a previously drilled pilot hole). Eccentricity causes distortion in the estimate for circle diameter. Therefore, an elliptical fit is recommended for high precision applications.

Taubin's ellipse fitting method was chosen because it is closed form and known to be highly accurate [1]. The algorithm generates the coefficients for the general quadratic curve used to define an ellipse,

$$ax^2 + 2bxy + cy^2 + 2dx + 2fy + g = 0.$$

(2)

Desired metrics for countersink measurement can be computed from these coefficients, for example

$$a' = \sqrt{\frac{2(af^2+cd^2+gb^2-2bdf-acg)}{(b^2-ac)\left[\sqrt{(a-c)^2+4b^2}-(a+c)\right]}}$$

(3)

$$b' = \sqrt{\frac{2(af^2+cd^2+gb^2-2bdf-acg)}{(b^2-ac)\left[-\sqrt{(a-c)^2+4b^2}-(a+c)\right]}}$$

(4)

where a' and b' are major and minor diameter, respectively [2]. An example of the Taubin fit with major and minor axes is shown in Figure 7.
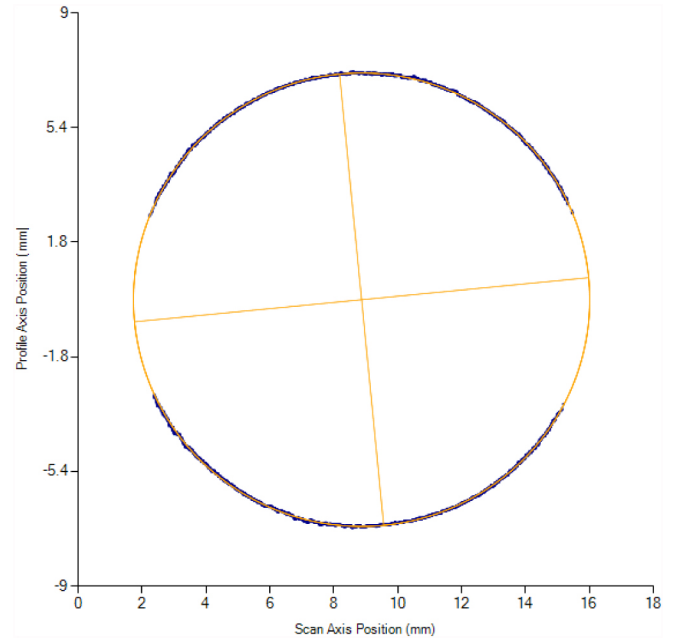

Figure 7. Taubin fit.

Outlier Filtering

Debris and cutting fluid on the countersink can introduce significant error in the system. The effect of debris on the determination of edge position is illustrated in Figure 8.
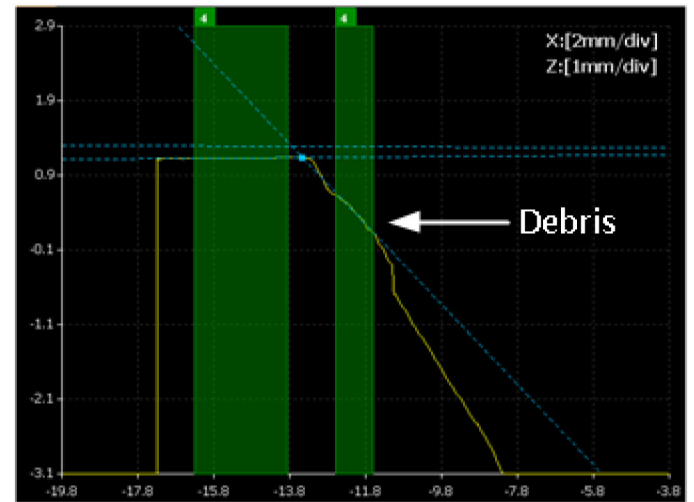

Figure 8. Distortion of the profile due to debris.

To counter this, an iterative outlier filtering algorithm was developed, shown in Figure 9. An ellipse is fit to the initial noisy data. All points with algebraic distance greater than a configurable tolerance from the ellipse are discarded. The process is repeated to convergence.
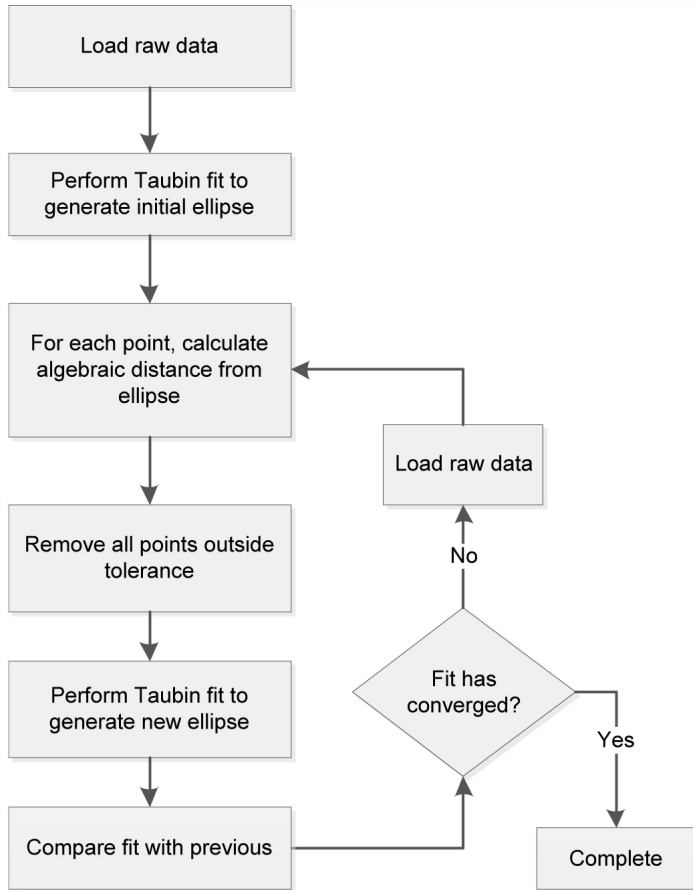

Figure 9. Outlier filtering algorithm.

It was empirically determined that suitable tolerance settings are proportional to the diameter of the countersink. Therefore, the tolerance is automatically chosen by the software as a function of the last major diameter found. Convergence typically occurs within 4 or 5 steps. The complete algorithm takes under 1 second on a typical PC. Figure 10 shows an example of the steps to convergence
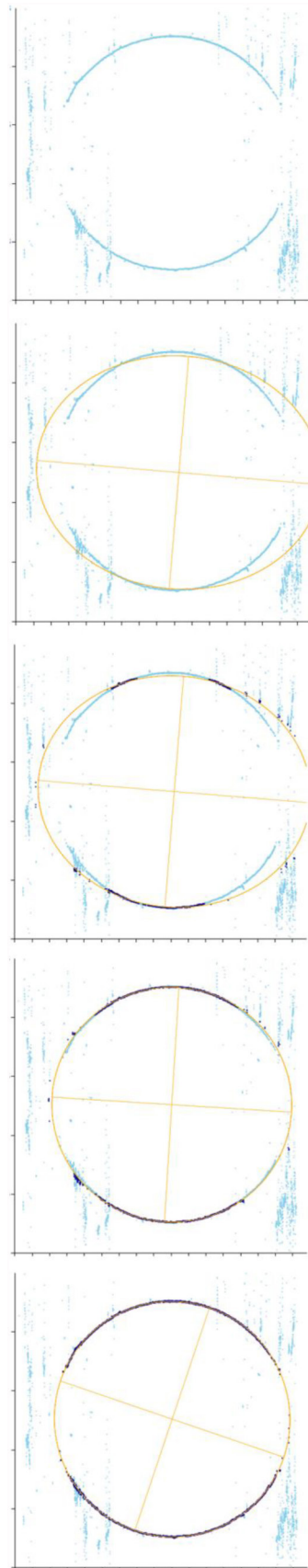

Figure 10. Each step of outlier filtering through convergence. Points within tolerance are shown in dark blue.

EXPERIMENTAL RESULTS

Experiments were performed to quantify the performance of the system on carbon fiber. The system was installed on a production gantry drilling machine. All experiments were done on flat coupons of varying surface type: unpainted, painted, and painted with integrated copper mesh. Holes were drilled and left dirty for measurements. The holes were then cleaned and measured again. Results include repeatability as well as accuracy with respect to a precision check-bolt depth measurement.

The particular application used for this analysis is intended to predict fastener flushness based on the countersink diameter measurement. Repeatability and accuracy statistics are computed after converting the countersink geometry to flushness of a precision check-bolt.

As stated earlier, surface curvature and poor normality while drilling will result in elliptical countersinks. For this reason, we use the minor diameter because this is where the check bolt will generally rest. Flushness is then estimated using the following equation:

$$\Delta d = \frac{D_c - D_m}{2 \tan \frac{\theta}{2}}$$

(5)

where D_c is the check bolt head diameter, D_m is the countersink measurement, and θ is the countersink angle.

Repeatability

For the repeatability experiment, 2 holes were drilled with a 5/16″ cutter at different CSK depths. The profilometer system was then used to measure each hole 30 times while the holes were still dirty with cutting fluid and carbon debris, as shown in Figure 11. The test was then repeated after cleaning the holes.

Figure 11. Holes with cutting fluid and debris used for the repeatability assessment.

Every conceivable means by which to affect the measurement stability was introduced. This included moving off to a random location prior to each scan as well as power cycling the CNC and laser controller every 10 holes. The resulting 3-Sigma repeatability is summarized in Table 1.

Table 1. 3-Sigma repeatability of the filtered laser profilometer measurement.

	Clean	Dirty
Hole 1	0.000021″	0.000037″
Hole 2	0.000017″	0.000013″

Rough Accuracy Assessment

For the purpose of this initial article, a check-bolt flushness measurement is used as a datum for a rough accuracy assessment. This is performed by placing a precision check-bolt with known chamfer dimensions into the hole. The distance between the head surface and the workpiece surface is measured using a height gauge as shown in Figure 12.
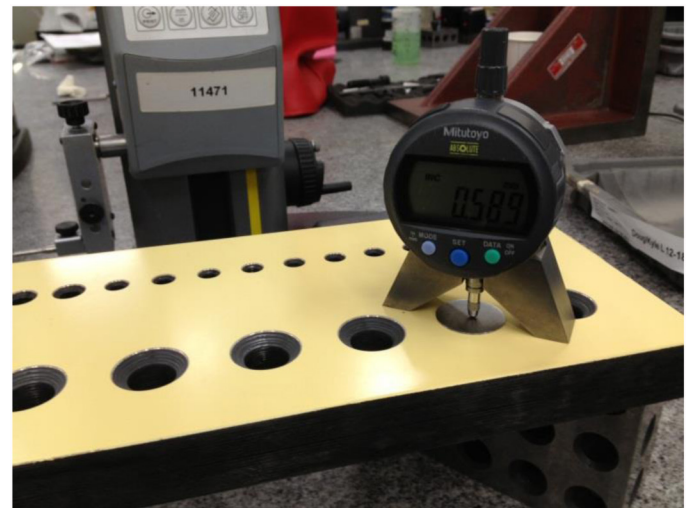

Figure 12. Check bolt and height gauge on a painted CFRP coupon.

Repeatability for the datum was found to be an order of magnitude worse than the laser, which makes this a poor datum for assessing accuracy. However, we provide these results as a minimum level of performance. The results also describe how well the laser method agrees with the widely accepted check bolt method regardless of what the true countersink diameter is.

Datum repeatability was determined by measuring each individual hole 7 times. The dominant source of error on CRFP came from surface flatness where the gauge base contacts the coupon. Therefore, for each measurement the height gauge was rotated such that the base contacts the coupon surface at a different location. Three sigma repeatability of the check bolt method was typically on the order of 0.0008″.

Tests were conducted for three different cutter sizes: 1/4″, 5/16″, and 5/8″ bore. All tests were performed on CFRP coupons. Three surface types were tested: unpainted, painted, and painted with integrated copper mesh. Ten holes were drilled for each configuration. Countersink depth was varied randomly across a .002″ range. The first hole was used to calibrate the laser, while the remaining nine were used to generate the statistics. Results are provided as 3σ worst case deviation from the check bolt flushness measurement:

$$E_{3\sigma} = |\bar{E}| + 3\sigma$$

(6)

where Ē is the average error, σ and is the standard deviation.

Figure 13 shows a typical example of the laser measurement, check bolt datum (average of the 7 measurements), and error bars representing the repeatability of the check bolt datum. A summary of the complete results are show in Table 2.
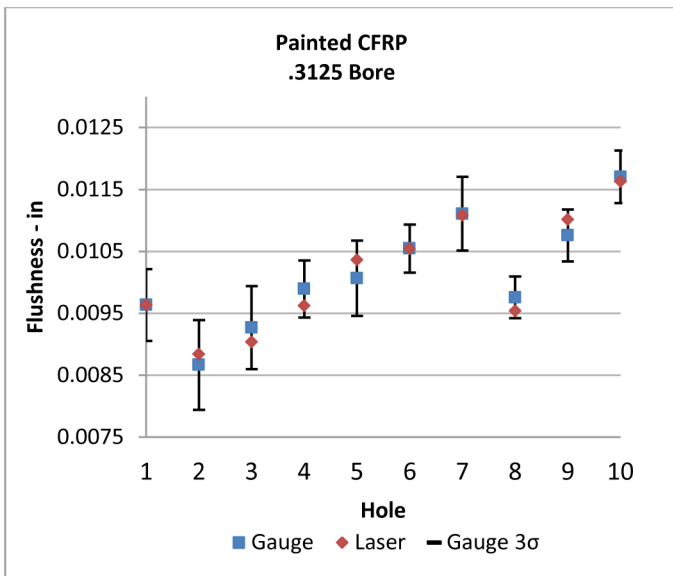

Figure 13. Flushness estimate from the laser measurement plotted with datum flushness and datum repeatability. Laser repeatability is too small to show at this scale.

Table 2. Worst case difference between the laser and check bolt data

	Bore (in)	$E_{3\sigma}$ (in)
Painted CFRP	0.2500	0.00058
	0.3125	0.00076
	0.6250	0.00075
Painted CFRP w/ Copper Mesh	0.2500	0.00050
	0.3125	0.00071
	0.6250	0.00093
Unpainted CFRP	0.2500	0.00036
	0.3125	0.00063
	0.6250	0.00070

This is our first attempt at an accuracy assessment for this system. Due to the poor repeatability of the check bolt method relative to that of the laser system, this test is meant only to provide assurance that the two methods agree within the datum's repeatability. We plan to follow up this paper after the system has been tested in production. Acceptance testing prior to implementation will include a more rigorous accuracy assessment.

CONCLUSIONS

Laser profilometry can be used for non-contact countersink diameter measurement. The method is highly repeatable and resistant to lube and debris. With filtering and post-processing, it is very likely to meet or exceed the performance of current technologies typically used in aerospace assembly.

Repeatability was found to be better than 40×10^{-6} in. The method agrees with the check bolt and height gauge datum within the order of the datum's repeatability of 8×10^{-3} in.

Further research will include a more rigorous accuracy assessment, performance data in a production environment, and performance data for other materials such as aluminum. The results are to be published in a follow-up paper.

REFERENCES

1. Taubin, G. (1991). Estimation of Planar Curves, Surfaces, and Non-Planar Space Curves Defined by Implicit Equations with Applications to Edge and Range Image Segmentation, *IEEE Transactions On Pattern Analysis and Machine Intelligence*, Vol. 13, 1115-1138.
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