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Interface Gap Measurement Using Low Coherence Interferometry

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Abstract

Large-scale aerostructures are commonly constructed using multiple layers of stacked material which are fastened together using mechanical methods. Ensuring the interface gaps between these materials are kept within engineering tolerances is of utmost importance to the structural integrity of the aircraft over its service life. Manual, right angle feeler gauges are the traditional method for measurement of interface gaps, but this method is tedious and mechanic dependent. A portable hand tool utilizing low-coherence interferometry has been developed to address these issues. The tool uses a right-angle probe tip which is inserted into a previously drilled hole and driven through the depth of the material. A line scan of data is collected and analyzed for the presence of interface gaps. To measure the consistency of the gap around the circumference of the hole, the tool is rotated by the operator and additional scans are collected. The tool is portable, can be operated by a single mechanic, and is capable of measuring different diameter holes by changing a radial index bushing.

Overall system accuracy is targeted at ±0.001" and achievable under most circumstances. A full system cycle, consisting of four scans at various locations around the hole's circumference, consumes approximately 40 seconds. There is no additional time required for data processing. The system stores the measured gaps and detailed plots of each scan for future analysis.

An extension of this technology has also been developed by automatically rotating the probe tip at several hundred RPM. This provides a 3D point cloud of the hole and enables measurement of additional features such as hole diameter, cylindricity, and detection of surface imperfections. This extended scanning technology is best suited for automated equipment where size and weight are less of a driving constraint.

Introduction

The accurate measurement of voids or gaps between layers of stacked material is important to ensuring aerospace components are assembled within tolerance and not subject to unnecessary stresses. Often this measurement has been accomplished using right angle feeler gauges, but this method is time consuming, tedious, and operator dependent. Electroimpact, in collaboration with Boeing, has developed a portable hand tool which utilizes a right-angle probe and low-coherence interferometry to address the shortcomings of the feeler gauge method. The right-angle probe is inserted into a previously drilled hole and a line scan of data is collected as the probe is mechanically driven through the depth of material. Distance and intensity data are collected and analyzed for gap detection and measurement. The system has the capability to locate multiple gaps and is suitable for use in various metallic and composite materials. The tool can be manually rotated in the hole to obtain several scans and determine gap size variability around the circumference of the hole. Several versions of the hand tool have been produced to address different hole diameters, stack thicknesses, and unique geometries of the parts to be measured. Novacam Technologies, Inc. has supplied the interferometer, right angle probe, and acquisition software.

System Overview

The Interface Gap Measurement Probe consists of three primary components: the hand tool, the control box, and the HMI. The hand tool is a portable device which is inserted into previously drilled holes and contains the right-angle probe. This hand tool connects via a small umbilical cable to the control box. The control box contains an interferometer, a PC for data processing, and a PLC for tool control. A touchscreen tablet connects to this control box via Ethernet or Wi-Fi and is used as the primary HMI. The system components can be seen in Figures 2 and 3.

FIGURE 1 Interface Gap & Right-Angle Probe

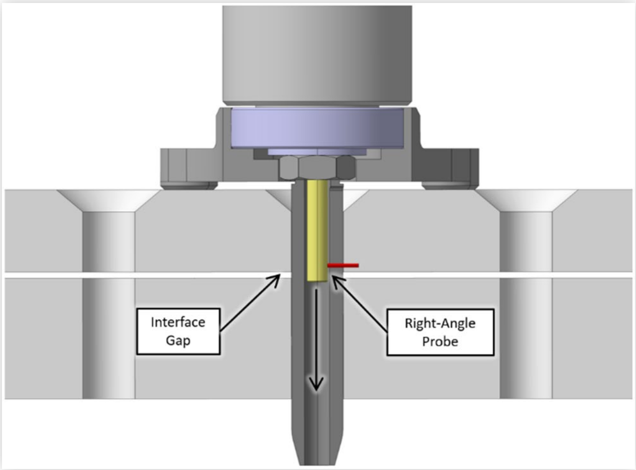


FIGURE 2 Interface Gap Measurement Probe Hand Tool and Tablet-Based HMI

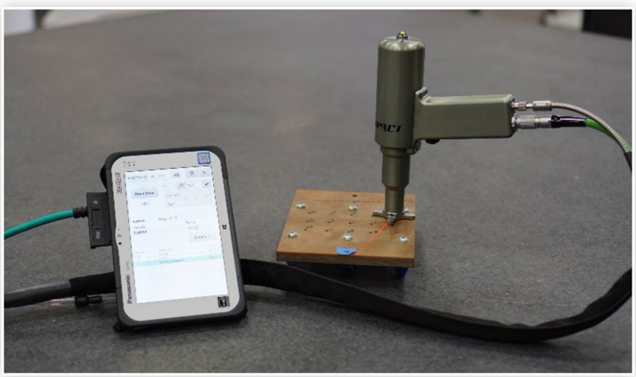


FIGURE 3 Interface Gap Measurement Probe Control Box

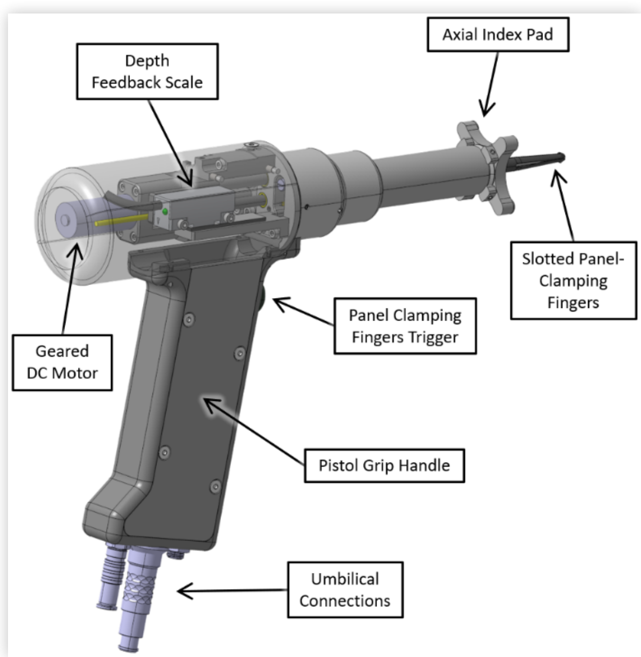
Probe tip movement is accomplished via a 6mm diameter precision ballscrew, geared DC motor, and a set of ground linear rods. Travel for the probe axis can tailed for the specific application. Accurate depth feedback is required for the control system to calculate gap thickness, so a depth feedback scale is included. The output of this scale is fed to the interferometer as well as the PLC. Detail on the internals of the hand tool can be seen in Figure 4.

Design Approach

Electroimpact, being primarily a manufacturer of large-scale aerospace assembly automation systems, is not frequently tasked with the design of small, light-weight hand tools. Design of such tools requires the engineer to have a mindset different from that of a standard machine designer. Simplicity in the design, careful component selection, and optimum layout are all of great importance in minimizing the tool's final form factor and maximizing usability.

Since the tool must be used in several different orientations, a pistol-grip design was selected over a pure cylindrical design. The majority of the tool components are manufactured of aluminum alloy for its light weight, durability, and its machinability to tight tolerances. To minimize tool complexity, all possible tool hardware is located away from the hand tool in the control box. A PCB breakout board is included in the pistol-grip handle which allows the tool sensors to be easily replaced without soldering the tool-side umbilical connector.

FIGURE 4 Hand Tool Components



Tool Indexing

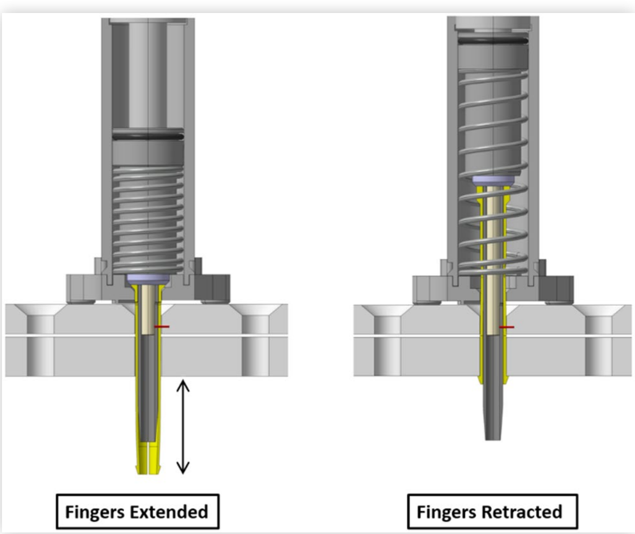
Reliable tool indexing in the radial and axial directions is important to ensuring accurate interface gap measurements. The probes have a somewhat narrow depth of field and thus measurements are best taken at the design focal distance. Acceptable results have been obtained with probes measuring as much as 0.040” off of their focal distance so further research into the limits of out-of-focus measurement needs to be completed to understand the limitations.

Radial tool indexing is accomplished using a bushing which is inserted into the hole to be measured. The bushing has a full-depth slot incorporated to provide the right-angle probe line-of-sight to the bore of the measured hole. The bushing doubles to as a protective sheathe for the somewhat fragile probe tip.

An additional feature that can be incorporated into the design is a pair of pneumatically actuated fingers which allow the tool to self-support in the hole. The design of the fingers is akin to that of a Cleco Fasteners with fingers that expand when retracted over a central mandrel. The fingers are retracted using spring force and extended using compressed air. This configuration is fail-safe, in that clamping force will be maintained if compressed air to the tool is interrupted. Air flow to the finger cylinder is controlled via a solenoid valve built into the body of the tool and an electronic push-button mounted to the tool handle. Figure 5 illustrates the pneumatic fingers in their extended and retracted positions.

Axial tool indexing of the tool is accomplished using a pad or foot which contacts the panel surface. The geometry of the pad is designed to maximize tool stability while avoiding any obstructions or adjacent holes that may be present in the measurement area. In most applications, the shape of the pad resembles a "plus" or "clover leaf" design.

FIGURE 5 Spring-Pneumatic Panel Clamping Fingers



Gap Measurement in Holes of Various Diameters

One possible method of measuring gaps in holes of different diameter is to use multiple hand tools with different diameter radial bushings. While this is effective, it is complex from an operator standpoint and expensive from a procurement standpoint. A more elegant solution is using a single tool and installing a specialized adapter bushing over the hand tool's primary bushing. Different adapter bushings are used for each hole size, with a wide range being possible. For example, a tool could be sized for 1/4" holes but using four bushings, could measure interface gaps in holes of diameter 5/16", 3/8", 7/16", and 1/2". The adapter bushings are held in place on the tool with the Cleco-style fingers or magnets. Slots in the offset bushings are aligned to the primary bushing slot using dowel pins or machined flats. Figure 6 shows an adapter bushing as it would install on hand tool’s primary bushing.

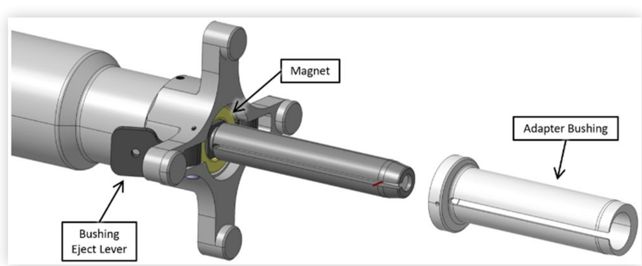
Data Acquisition

The system operates on the technique of frequency domain interferometry. A fast-sweeping laser source which operates in the infrared spectrum at a wavelength of 1310 nm is sent via optical fiber to the probe tip as well as a fixed reference mirror. Signal reflections are combined, and an interference pattern is created and observed by a detector. The observed spectrum is then converted to the time domain using a Fourier transformation. Sent and received light signals are colinear which reduces the need for multiple optical fibers and allows the measurement of sharp edges like those that occur in interface gaps. The acquisition rate of the system is 100 kHz which far exceeds the needs for interface gap measurement [1].

A fiber-optic line bundled in the tool's umbilical cable, connects the interferometer to the probe. The interferometer, probe, and acquisition PC are purchased from Novacam Technologies, Inc.

Two streams of data are received from the interferometer/acquisition software. One is a depth scan which provides information on the distance from the probe tip to the side of the hole and the second is an intensity scan which provides a measurement of received light intensity. Either or both of these data streams can be utilized by

FIGURE 6 Offset Bushing for Gap Measurement in Different Diameter Holes



the data analysis software to determine the presence of a gap and measure its size.

Data Analysis

A custom PC application is responsible for data processing and analysis, communication to the PLC for tool control, and the operator HMI. The application receives the distance and intensity data from the interferometer/acquisition software and uses various algorithms to find the location and size of the interface gap. The raw data received contains a certain level of noise so the data is filtered and smoothed as the first step in processing. Figure 7 shows a plot of example distance or intensity data with respect to depth. A plot such as this is generated for each scan and can be used by the operator to visually see the location and size of the measured gap(s). For simplicity in production use, it may be prudent to withhold this information from operators and purely display the measured gap size.

Different materials require different agoritms and techniques for proper gap detection and measurement. Operators are able to use the HMI to select the material being measured and the software will use the algorithm and settings best suited.

Accuracy and Repeatability

Overall system accuracy is targeted at ±0.001" and in most use cases has been found to meet or exceed that goal. Verification of the system accuracy is accomplished using measurements taken in precision test articles and/or calibration ring gauges. Table 1 shows the readings from a 0.1285" (#30) hand tool measuring a CFRP test panel. Three different gap sizes were measured, each a total of twenty times. The tool was rotated in the hole four times per test to gather four different line scans of data. The largest gap observed during the four scans was recorded as the measured gap. This approach was found to provide the most accurate results since holes in composite do not always have a clean edge break and small particles of material can be present inside of the interface gap.

Figure 8 is a scatter plot of the twenty measurements taken in the three gap sizes and Figure 9 shows the error in the measurements.

TABLE 1

Nominal Gap Size (in)	Average Measured Gap Size (in)	Average Error (in)	Std. Deviation (in)
0.0050	0.0051	0.0003	0.0004
0.0080	0.0076	0.0005	0.0004
0.0300	0.0296	0.0006	0.0004

FIGURE 7 Plot of Example Data

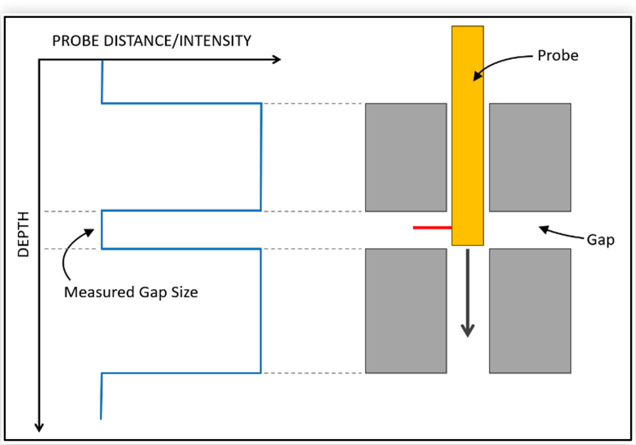


FIGURE 8 Gap Measurements in CFRP Test Coupon

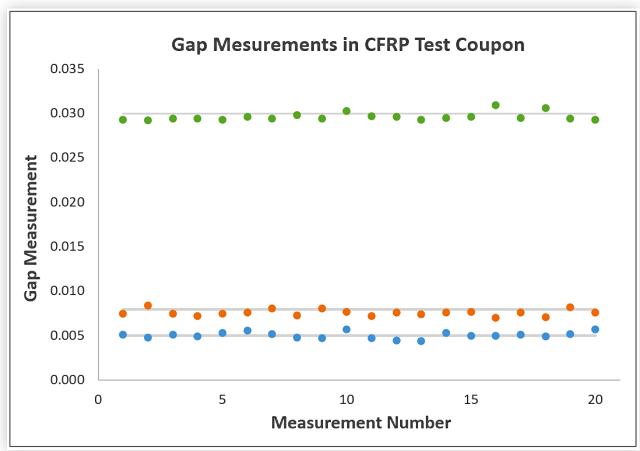
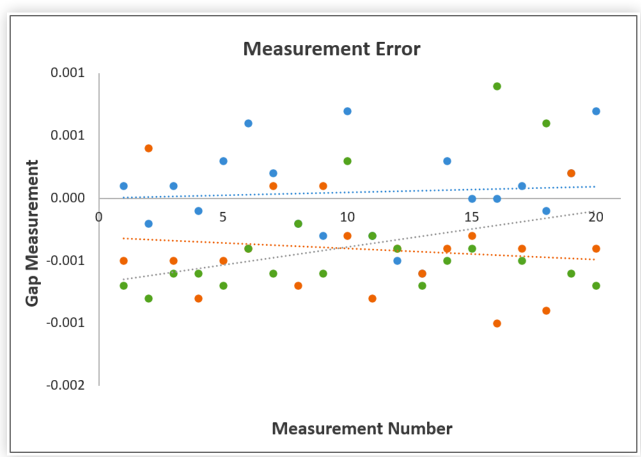


FIGURE 9 Measurement Error



Calibration

Much like industry-standard contact hole probes, the Interface Gap Measurement Tool uses gauge rings to correlate measured gap size to a known standard. The tool is inserted into the gauge ring, a measurement obtained, and the measurement compared to the gauge's gap size. A fixed offset can then be applied if needed. More elaborate calibration could be implemented but has not currently been deemed necessary. Frequency of calibration is up to the end user, but a daily check with a gauge ring of each hole diameter is prudent. Figure 10 shows the hand tool with a calibration ring installed.

Future

Further development of the Interface Gap Measurement Probe will yield a more integrated design with reduced size and weight. Improvements in the useability can be made by incorporating features such as a tool-integrated display or materials and geometries which offer better ergonomics. As higher quantities are desired, the reliance on off-the-shelf components will be reduced and a more optimized tool can be produced. In collaboration with Novacam Technologies, a size and cost reduction of the interferometer hardware is also being pursued.

The same base technology used in the gap measurement system can also be used in the measurement of other hole attributes. By spinning the probe at several hundred RPM, a 3D point cloud of data can be obtained and fed into commercially available metrology software for further analysis. Attributes such as diameter, cylindricity, and surface defects can be obtained. Multiple systems like this have been developed by Electroimpact and implemented in an R&D environment.

Both the linear scan gap detection system and the system which includes probe rotation can be installed on automated machine tools with relative simplicity. The inclusion of the rotation hardware drives additional size and weight and thus that system is best suited on automated machines rather than as a portable hand tool.

FIGURE 10 Hand Tool with Calibration Ring

Conclusion

Electroimpact, in collaboration with Boeing, has developed an automated tool which can accurately measure the interface gaps between multiple layers of stacked material. The tool offers improved accuracy relative to alternative hand methods while consuming less time and producing less operator fatigue. Continued development is ongoing with future integration into automated machine tools for the measurement of additional hole attributes such as diameter and cylindricity.

Reference

1. Novacam, "How Low-Coherence Interferometry (LCI) Works," April 9, 2021, https://www.novacam.com/technology/how-lci-works/#:~:text=Low%2Dcoherence%20interferometry%20(LCI)%20is%20a%20non%2Dcontact,an%20optical%20fiber%20for%20interpretation.

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Definitions/Abbreviations

HMI - Human Machine Interface
PLC - Programmable Logic Controller
CFRP - Carbon Fiber Reinforced Plastic

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