Gapman® $_{Gen3}$ Electronic Gap Measurement System for Aircraft Applications

For years aircraft assembly and structural component manufacturers have been using traditional contact methods (plastic shims, feeler gauges, step gauges etc.) to measure gaps during the production and final assembly of commercial and military aircraft. Hundreds of gaps between metal/metal, metal/Carbon Fiber Reinforced Polymer (CFRP) and CFRP/CFRP surfaces must be measured and controlled during the production to determine whether liquid or solid shimming is required. These gaps can be found in a wide variety of applications located throughout the aircraft structure from the front passenger doors to the vertical stabilizer. (see Figure 1 for typical applications)

Figure 1: Typical Aircraft gap measurement locations

Process control improvement drives new gap measurement techniques

Due to the increased standardization of process improvement methods such as SPC and Six Sigma, aircraft structural component manufacturers from Alenia to Lockheed are adjusting output specifications from their measurement instrument suppliers. The new standards require the measurement, data capture and documentation of an ever increasing number of physical measurements such as gaps, holes and parallelism in their manufacturing and assembly processes. Traditional gap measurement methods such as feeler gauges and plastic shims cannot meet the new quality specs for accuracy and repeatability and are not able to automatically record and store error free data.

Engineers have also found limitations and major reliability problems with these old methods. Shims and feeler gauge suffer from inadequate accuracy. Plastic shims can vary in thickness by 7.6 microns and both these and feeler gauges cannot meet required operator-to-operator repeatability levels. In addition, accuracy is reduced over time due to shim wear from constant rubbing against hard surfaces which can also potentially cause damage to the target surfaces.

It is now common for these users to perform Analysis of Variance between Groups (ANOVA) Gauge Repeatability and Reproducibility Studies (Gauge R&Rs) to compare the capability of traditional measurement methods versus more modern methods such as digital capacitive non-contact gap sensor instruments. A leading aircraft structure manufacturer recently tested and concluded that feeler gauges could not meet their Six Sigma requirements. Specifically their Gauge R&R concluded that mechanical gauges totaled 45% measurement dispersion versus 20% or better for Capacitec gap gauges. Since feeler gauges showed a measurement dispersion of greater than the required 30% minimum for Six Sigma, they were forced to change. The solution was to use a Gapman® capacitive gap measurement system that they call their "electronic feeler gage". (See Figure 2.)

Figure 2: Photo of Gapman® $_{Gen3}$ with remote spring contact wand

Development of the Capacitec Gapman$_{Gen3}$

Capacitec specializes in capacitance measurement which is the core technology used exclusively in their line of non-contact displacement, gap, hole and parallelism sensors and sensor systems.

Principle of Operation

Capacitive reactance is proportional to the distance between the sensor and the target while the physical principle used to make distance measurements is based on the variation of capacitance between the sensor and its target. See Figure 3

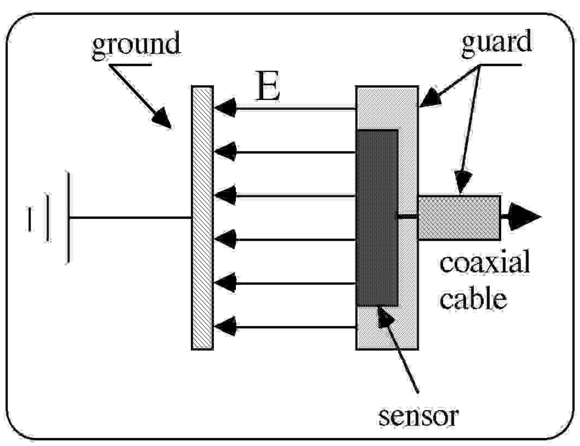


Figure 3: Capacitive technology

Aircraft structure gaps are measured with two capacitive displacement sensors mounted back-to-back at the end of a flat wand. Each sensor has a central sensing element with a typical diameter of between 2 to 5 mm (0.079" to 0.197") depending upon the gap range required. The larger the sensor diameters, the larger the linear range of the gap sensor wand. A ring guard layer surrounds both sensors that serve to focus the capacitive charge field to a grounded target. Each sensor has a 100% shielded coaxial cable.

When positioned parallel to an earth grounded or conductive target, the sensor measures a capacitance proportional to the air gap. When the signal is input to a specialized signal conditioner amplifier, the output range can be linearly ratioed between 0 – 10.000 VDC. This resulting output has a ratio of one part in ten thousand. For example a full-scale range of 0.254 mm (0.010") divided by 10,000 yields an output resolution of 250 nanometers/mVdc (1 micro inch/mVdc).

Sensor wand technology development

Non-contact semi-rigid sabres

In the 1980s Nuclear Fuel Rod manufacturers were dissatisfied with the reliability, accuracy and overall performance of the use of mechanical contact gauges to measure thin gaps between the hundreds of individual rods in fuel rod assemblies. See Figure 4. Babcock & Wilcox, Westinghouse, Areva and others approached Capacitec to develop a newer technology method using their years of experience in capacitance measurement.

Figure 4: Typical Nuclear Fuel Rod Bundle

The resulting Capacitec design consisted of the two aforementioned capacitive non-contact displacement sensors installed on mating opposite sides of a *metal sabre* and calibrated to two custom capacitive amplifiers. After the fuel bundles were assembled, these semi-flexible half-meter long gap measurement sabres were automatically inserted between rows of 16 fuel rods at several locations along the 6-meter height of the fuel bundle. Based on the success of this new design's reliability, repeatability, high accuracy and durability the Capacitec non-contact gap measurement system is now the standard measurement technology for fuel rod manufactures across the globe.

Flexible Sensor Wands

The development of flexible gap measurement wands was born in the specialty Thin Film liquid coating industry. As the demand for more uniform and thinner film products accelerated, manufacturers such as 3M, Kodak and DuPont needed to find new methods to control the coating consistencies across their 2 to 3 meter specialized coaters. Research proved the direct relationship between coating thickness consistency and the ability to set very accurate gaps in the coater dies prior to production. Capacitec was approached to develop new customized very thin flexible gap sensor wands to replace plastic shims.

The resulting Slot Die Coater Gap Measurement system allowed users to maintain a uniformity of ±0.25 microns (10 micro inches) across coater dies helping them better control their nanometer level coating thicknesses. See Figure 5.

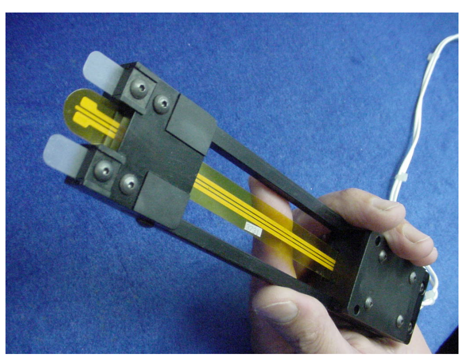
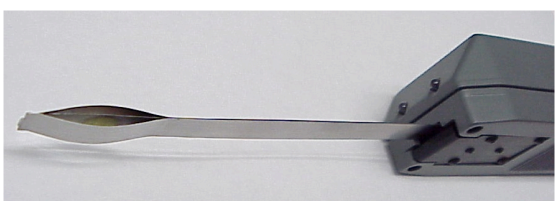


Figure 5: Very thin flexible wand with wand positioning holder

These flexible Kapton® gap sensor wands were further adapted to operate with the Gapman® to meet the requirement of accurately and automatically measuring gaps in aircraft structures.

Self grounded semi-rigid contact sabres

Self-grounded semi-rigid contact sabres were designed in response to GE PowerGen request to develop a better way to measure gaps between the fan blades in a Gas Turbine and the exterior enclosure. Again feeler gages were the existing measurement method and did not meet Gauge R&R and Six Sigma documentation requirements. The particular challenge for Capacitec in this application was how to measure gaps between a conductive and non-conductive target. The solution was the creation of a Spring Contact Wand where the matching upper and lower self-grounded moving metal springs serves as the conductive target. This system eliminates the need to ground targets while offering a new solution to reliable gap measurement where one or both targets are non-conductive. This technology was further developed to work with the Gapman® in both the integral and remote holder configurations. See Figure 6.



Gapman® $_{\text{Gen2}}$ with integral spring contact sabre

Gapman® $_{\text{Gen3}}$ with remote spring contact sabre

Figure 6 Gapman® configurations with self grounded spring contact sabre

Sensor Selection

The capacitive gap sensor wand model selection is application driven and chosen in reference to the following factors: minimum gap, gap range, target material combinations (metal/metal. metal/CFRP, CFRP/CFRP), difficulty of access to target etc. There are dozens of standard models of both flexible wands and spring contact sabres along with the option of developing custom models according to customer needs.

Flexible wands

Kapton® flexible wands are typically used to measure the thinnest gaps and where the flexibility of the wand improves accessibility to the target. The thinnest cap measurement available can be found in Model GPD- (3X1) I-A-225 that offers a range from 0.15 mm (0.006") to 1.0 mm (0.0394"). The popular Model GPD-4.5 (.0075)-A-250 has a range of 0.20 mm (0.0078") to 3.0 mm (0.118"). Other models can be specified to have a range up to 10 mm (0.394).

Thin Sensor Wand GPD-(3X1) I-A-225

Size: 14 mm x 225 mm x 0.150 mm
(0.55"x 8.85"x 0.006")

Thin Sensor Wand GPD4.5(.0075)-A-250

Size: 14 mm x 250 mm x 0.190 mm
(0.55"x 9.8"x 0.0075")

Figure 7: Typical standard flexible wand options

Figure 8: Gapman® $_{\text{Gen3}}$ *with integral Flexible Wand measuring very thin gaps CFRP/CFRP*

Self grounded spring contact wands

Spring contact wands are typically used in applications where: one or both targets are non conductive; a target size is < 2mm or the surface or shape of the target is irregular. These are also the most popular choice for CFRP/CFRP applications where the minimum gap is >0.64 mm (0.025″). The Spring Contact wand Model GPD-5 (0.22)-A-150 has a range of 0.64 mm (0.025″) to 3.0 mm (0.118″) while the range of the GPD-10 (.034)-A-350 is 0.86 mm (0.034″) to 10.0 mm (0.394″)

Spring Contact Wand GPD-5(0.22)-A 150

Size: 14 mm x 150 mm x 0.86 mm (.551″x 5.9″x 0.034″)

Spring Contact Wand GPD-10(0.34)-A-350

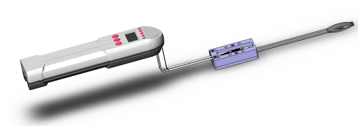
Size: 27 mm x 350 mm x 0.86 mm (1.063″x 13.8″x 0.034″)

Figure 9: Typical Spring Contact Wand options

For larger gaps such as the gaps between trailing edge flaps and the wing where the gaps typically run 25mm ±5mm (1″ ± 0.2″) a custom wand can be offered. In this case a non-contact or spring contact wand is built onto a 15 mm shim with a set of GPD10 sensors giving a range of 15mm to 25mm.

The selection of integral or remote wand mounting configuration to the Gapman® is according to customer preference. See examples in Figure 10.

Integral flexible wand



Remote spring contact wand

Figure 10: Sensor wand mounting configurations

From Gapman®$_{Gen1}$ (analog) to

Gapman® $_{Gen2}$ (digital) to

Gapman® $_{Gen3}$ (serial/wireless)

Figure 11: Gapman® Generations 1 to 3

Gapman® $_{Gen2}$

The Gapman® $_{Gen2}$ model was introduced with flexible wands in 1996. The remote vs. integral configuration and availability of spring contact wands were introduced later. Today most commercial and military aircraft manufacturers world wide use the Capacitec Gapman® $_{Gen2}$ to measure and control gaps that typically range from 0.20 mm – 3.0 mm (0.0078" - 0.118"). In the assembly of tail sections, a Gapman® $_{Gen2}$ with flexible wand is used to measure gaps 20 cm (7.87") inside of the subassembly. A flexible wand can also be seen accessing difficult to access targets See Figure 12.

Figure 12: Gapman® $_{Gen2}$ showing flexible wand in action

The self-grounded spring contact saber is often used to measure gaps between targets where on or both sides is composed of CRFP. In another application example gap readings from the Gapman® $_{\text{Gen2}}$ are sent to a CNC machine, which manufactures custom shims that fit perfectly in the void between two structural components of the aircraft.

Gapman ®$_{\textbf{\textit{Gen3}}}$

The Gapman® $_{\textbf{Gen3}}$ was introduced in late 2010. Among the main design enhancements of the "next generation" Gapman® $_{\textbf{Gen3}}$ are higher resolution output (0.00001"/ 0.254 μm) with ±0.05% FS (12.7 μm) typical accuracy with a GPD-5F wand; 10,000+ data point logging and storage capabilities; battery life doubled (now 22 hours minimum with 3 AA lithium batteries); and simplified PC user interface software to allow control of the outside button functions and storage of gap measurement data through USB or Zigbee wireless transfer.

With a compact form factor measuring just 2.2" x 8.7" x 1.1" (56 x 220 x 28 mm) and weighing less than one pound (454 grams), the Gapman® $_{\text{Gen3}}$ features the same high-precision dual capacitive sensing technologies for position-compensated measurements as its predecessor, with components housed in a factory floor tested, highly rugged enclosure. Using standard and custom sensor probes that are backwards compatible, Gapman® $_{\textbf{Gen3}}$ allows for easy insertion into gaps as thin as 0.150 mm (0.006").

The Gapman® $_{\text{Gen3}}$ records and stores data points for easy transfer to SPC, in support of Six Sigma and other quality systems. Other "next generation" enhancements include a bright blue alphanumeric Active Matrix OLED display; external menu selection buttons for millimeters/inches; a calibration button, to adjust to the standard of a known gap; and inclusion of an industry standard USB Type A combination data output and external power port. With its user-friendly design enhancements, the "next generation" Gapman® $_{\textbf{Gen3}}$ can be used to effectively measure gaps within a wider range of aircraft applications, including aircraft manufacturing and assembly operations; metal and rigid composite surfaces (CFRP) and aircraft engine and rebuild. Other applications include flexible solar panel lamination; coater roller-to-roller parallelism; film production; and any other non-contact gap measurement application characterized by minimal gap tolerances and complex assemblies.

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