ATX LABS TECH BRIEF

The Art of Microwave Connector Gaging for Optimal Field Calibration

No Matter the Technique, Gaging a Microwave Connector Interface for the Determination of Pin Depth Requires a Combination Repetitive Sampling and Uncertainty Analysis

There are three approaches to gaging a microwave connector interface, where gaging is defined as measuring the grade difference between the two electrical planes of the connector that are the terminal extensions of the two conductors of TEM transmission line.

Introduction

A conventional miniature connector in full and sectional profile would look something like figures 1 and 1a.

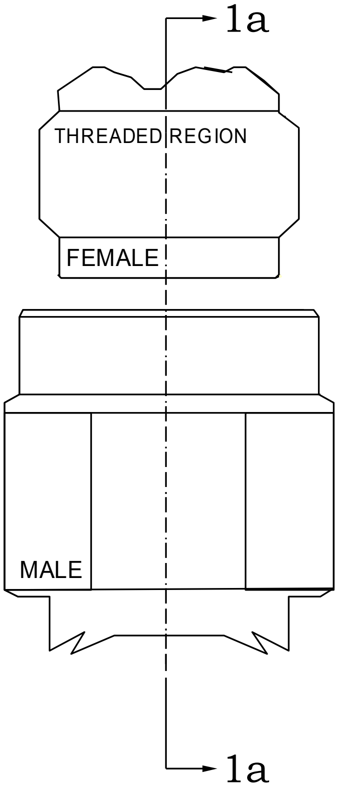

FIG. 1

Figure 1a is the sectional view of figure 1, and it is understood that this is a 2D slice through a three dimensional, volume. If the sectional slice were rotated 360 degrees, a solid 3D volume would be created..

The three approaches to gaging all look to establish the difference in grade between features internal to the connector that are subject to Standards like IEEE287LPC/GPC, (lab and general precision) and MIL-STD-348B, to cite two of the common ones. Manufacturers will often build to proprietary standards unique to their design philosophies.

In general, the grade difference subject to Standard is the difference between planes (2a) and (2c) in the male, and (4a) and (4c) in the female – that being the differential grade between pins or sockets on the one hand, and the top plane of the surrounding coaxial body, referred to as the reference plane, on the other. Per Standard IEE287, this differential grade must be *no greater* than the “maximum allowable pin depth” as defined within the Standard.

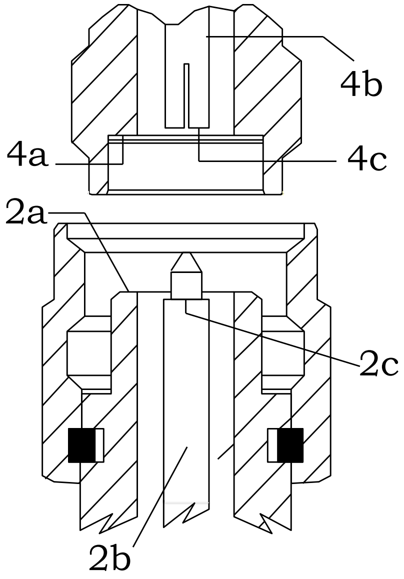

FIG. 1a

Gaging Basics

The three approaches alluded to above are the following: **[i]** the use of a *free hand* probing means to measure the depth of the male pin's shoulder (2c) or socket's front plane (4c), relative to (2a) outer plane in the male and (4a) in the female. This approach normally takes the form of a conventional dial indicator re-purposed as a depth indicator for free style hand use – similar in principle to depth gages for measuring tire tread wear – though more precisely and accurately machined to this purpose. **[ii]** the use of the same instrument cited above, re-purposed for hand use, but now given a threaded means to engage the male and female connectors as they would be engaged in actual mating. **[iii]** a noninvasive approach using an optical profiler to measure grade differences *without* physical contact between the profiler and the differential planes being measured for recession of the center conductor relative to the outer conductor.

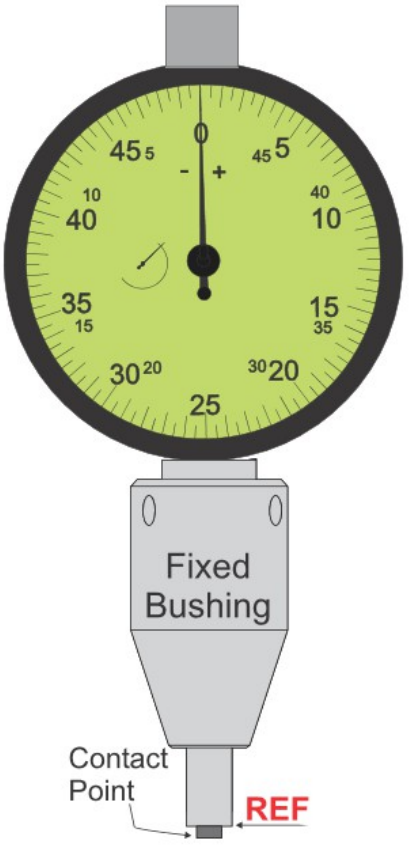

Figure two

A free hand gage, in the most general terms, looks something like figure 2. In this figure a common machine shop indicator is fitted with a fixed bushing and a custom contact point, the former intended to establish a datum by resting on the reference plane, either (2a) or (4a) in figure one. So the “gage” is nothing more than the combination of a conventional part that has been re-purposed for hand held use. Normally, a dial indicator would be used on a vibration free stand in a lab, without any attachments, to measure the variation in a surface contour. If the gage were threaded to engage the connector in the same manner as a male connector threads to a female, the gage in figure two would have a male or female threaded bushing at the probing end for gaging one or the other gender.

When a host indicator to which a custom bushing and contact point are added, the host has already been calibrated traceably in a lab under ISO17025 constraints, under vibration free conditions, and on a stand – and those conditions do not reflect hand held field conditions. Moreover, the most common use of a dial or digital indicator is with reference to a datum that is not defined as part of the indicator – as is the case when a gage bushing is manually seated on a microwave connector's reference plane by a hand).

By way of example, lets suppose a GD&T specification for perpendicularity were 0.1 inches. There will be more discussion below with specific reference to the tolerances called out by Standard For now let's frame the discussion in terms of how dial and digital indicators are normally used in machine shops. Perpendicularity means that if you draw two lines perpendicular to a given datum, between which a surface resides, that surface is constrained by spec to fall within those lines to meet the perpendicular spec, as illustrated in **figure three**.

To check for perpendicularity, as illustrated in **figure four**, the datum surface would be placed flushly to a angle block that has an extremely tight 90 degree tolerance, and the block would be sitting on a granite surface with an AA flatness spec of about 50 millionths of an inch. The bottom of the fixture holding the dial indicator has a similar flatness spec. If one then slides the fixture over the surface, then any deviation from perpendicularity would be observed in readings on the dial indicator, for example, in tenths (or 0.0001 inches).

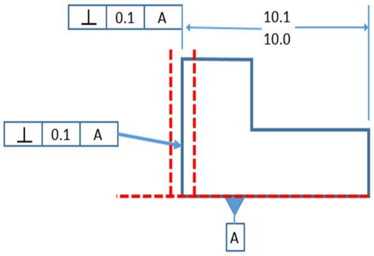

Figure three

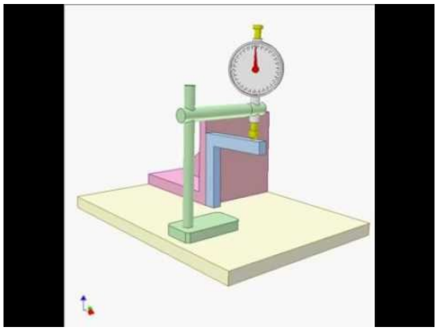

Figure four

In this case, a common use, the dial indicator is slave to other fixturing conditions independent of the indicator. The accuracy of the indicator is as good as the accuracy of the fixturing and the quality of the instrument. Historically, dial indicators are used under exacting machine shop conditions, often in controlled temperature environments in a QC department, and are not hand held but rather engaged at the stem (8mm or .375 inches) or by a lug in the rear of the indicator. Under these conditions the user relies on the calibrated accuracy of the instrument and assumes the fixturing and conditions of use add little additional uncertainty.

Hand holding introduces a significant challenge, namely, how to account for the added uncertainty which can be broadly framed in terms of *repeatability* – a type A component measured in statistical terms. With this in mind, consider the three approaches to using the dial indicator as a re-purposed tool for hand placement on a datum – the reference plane of a small connector – to measure a grade difference between a surrounding datum and a pin or socket plane.

With regard to using the threaded approach with best of breed gages, Keysight has for many years offered the following warning in all of its calibration kits and cable manuals, in bold type: “**Do not use the gages for precise pin depth measurements.”** They go on to assert : [i] “The connector gages are only capable of performing coarse measurements. They do not provide the degree of accuracy necessary to precisely measure the pin depth of the cable connectors.”; [ii] “Only the factory — through special gaging processes and electrical testing — can accurately verify the mechanical characteristics of the cable connectors.”[1] Under case 8282229173, Xiaoye Chen, an inside applications engineer for Keysight, discloses that Keysight at the factory uses a Zygo white light interferometer to measure pin depth – this being the third approach mentioned above.[2]

In light of the previous remarks, the following characterization makes sense regarding the three approaches to gaging.

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The Three Approaches: A Closer Look

Optical Approach: This has the advantage of removing the observer and his mechanical instrument – thus avoiding the so called observer effect, sometimes called the Heisenberg Effect after quantum physicist Werner Heisenberg. This approach is many orders of magnitude more costly than the other approaches – generally running $25K to over $100K.

With this approach, the observer is measuring a separation between two planes in the absence of a loading condition. However, this separation is not invariant with loading. Since loading effects are only realized upon actual mating or the simulation of mating with a threaded gage, any non-invasive technique will be measuring pin depth of the as-machined article. So what an optical, non-invasive technique is by definition accomplishing is a full characterization of the difference in grade between the outer conductor and inner conductor – and by doing so will be captured by literally *seeing* the grade differences due to the machine tolerance of the connectors.

A careful optical mapping of the two mating planes internal to a connector (pin and outer coaxial plane) will thus reveal the actual grade differential. But since this grade differential is a complex function of the machine tolerances of the connector, a judgment protocol must be in place to interpret how the two planes, now fully characterized as to grade difference, will interact with a another connector during mating. This must be done to decide if the grade difference mapped in its full complexity conforms, or not, to the "maximum allowable pin depth" called out by Standard. One imagines, since the connector features are inelastic solid materials, that the smallest recession will be the value noted for compliance.

Threaded Approach: This has the advantage of measuring recession in the presence of a real load that mimics the nature of the load when two connectors are mated after torquing to common values like 8 in-lbs and 12 in-lbs. This approach has an obvious cost advantage over the optical approach. On the downside, torque wrenches have some variability in torque that translates into additional uncertainty that should be added into an uncertainty budget. Also, if the argument that non-contact gaging eliminates observer effect, making it the Cadillac of gaging schemes, then the threaded approach would be based on the inverse of this logic – which implies that the two approaches need to be reconciled. Moreover, threaded gaging is inherently a hand held sampling procedure where a blunt instrument identical in scale to the surface being probed imperfectly samples a plane that has a tolerance. This tolerance – including the technique of the user - now introduces a strong Type A repeatability uncertainty. Finally, threaded gaging is relatively slow due to the threading and torquing constraint.

The Trial One table on page 6 shows the recession readings for a 1.85mm connector using a Keysight gage. There is a maximum min/max delta of one tenth, or 0.0001 inches. That is quite common and can be attributed to variations in torque, variations in surface contact as a function of final seating relative to contour, and variations in hand held discipline and consistency during gaging. Variations up to 3/10ths are not uncommon. The sample standard deviation in this case is 5e-05 with a standard error of 2.24e-5. The average is 0.00085, with a 95% probability of falling between .00081 and .00089, rounding. This is without factoring in the underlying calibrated uncertainty of the instrument itself.

The Free Style Approach: In this approach the user manually places the front end of the bushing on the connectors reference plane, allowing the contact point to fall into place on the pin or socket under about 2 ounces of force. As opposed to actual mating or threaded gaging, in free style gaging the load on the reference plane will be low – in the range of 8 to 32 ounces. This approach is faster than threaded gaging, allowing more measurements per unit time, thus increasing the frequency of sampling. It does, however, take some skill and the user must grow accustomed to manually positioning the gage. If non contact gaging is the Cadillac by virtue of removing the observer effect, then free style gaging – which puts a lighter load on the connector due to the avoidance of a torquing means – might have a similar though not as strong a rationale supporting it.

That said, the effect of loading the reference plane as done in actual mating cannot be ignored. Thus in free style gaging the loading effect, both lighter and potentially more variable than threaded engagement, is compensated for by placement skill. The object in all methods of gaging is to identify the minimal grade difference between conductor planes. Therefore anyone using a free style gage, notwithstanding the virtue of speed, cannot count on loading to facilitate alignment. Rather, careful placement to find best recession is accomplished by orientation of the gage. This will be expanded below when considering the machining and tolerance criteria in compliance standards.

For most users only threaded or free style gaging would be appropriate, mostly by virtue of cost. The choice between the two is a matter of user preference. The question to be explored below is whether we can extract anything from Standards like IEEE287LPC/GPC to provide guidance as to what might be considered best practice when gaging. IEEE287 does not express a preference for one gaging technique over another, and offers no guidance on measuring recession. For simplicity, the foregoing discussion will only make reference to IEEE287 GPC and LPC.

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A Closer Look at the IEEE287 GPC/LPC Standard

With reference to recession, IEEE287 simply defines a recession boundary as indicated briefly above. For example, 2 mils is the recession limit under IEEE287GPC for any of the subminiature families from 2.92mm to 1.85mm, male or female, and 5/10ths, or 0.0005 inches, or half a mil, is the recession limit for the same families under LPC constraints. When 287 uses the phrase

“***maximum*** allowable pin depth” in all footnotes where pin depth is specified, it is reasonable to assume that this means the ***as machined,*** or as found condition, yielding a recession of no more than 0.0005 or 0.002 under LPC and GPC respectively during actual mating.

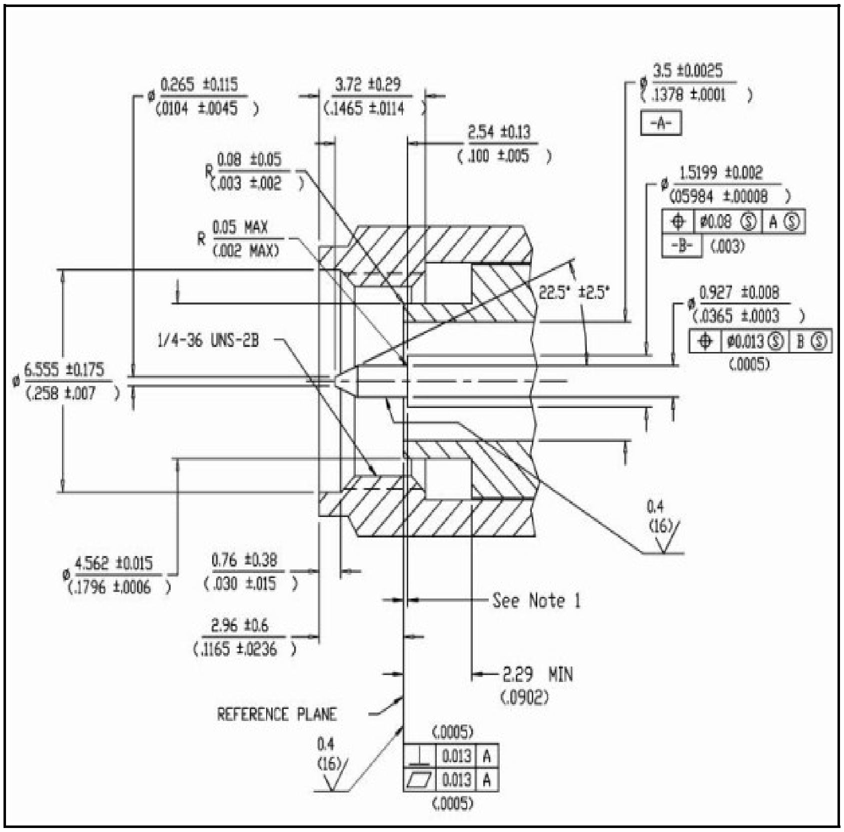

Figure five

If a manufacturer machines a center conductor and outer conductor (both cylindrical parts commonly turned on a Swiss lathe) and then uses a PEI slug to fix spatially the two components, the finished product shall conform at the point of assembly – ***as machined*** - to the 287 Standard.

Thus the as machined pin depth is used to predict probable conditions under use during connector to connector mating. However, conditions during gaging with a given connector gage may not perfectly predict pin depth when a connector is mated to another connector given variations in alignment of the mating planes. That said, a gaged approximation of pin depth with uncertainties is our only guide, so all gage techniques must attempt to seat and orient the connector under gage in a manner that approximates conditions of use.

This raises the following questions: [i] what is the as machined condition of a connector, and [ii] does it suggest anything about best practice when gaging?

To answer the above, consider not just the “maximum allowable recession” spec, but consider too the nature of the machine tolerances and finish that are called out in the Standard. Examining **figure five** taken from the 287 specification, the front plane, per GD&T call-outs, shall be flat to within 0.0005 inches (0.013mm). Even though the standard calls out a datum for this, that is likely incorrect since flatness is not datum specific. The GD&T spec also calls out perpendicularity of 0.0005 inches relative to datum A, the main connector axis. This is useful information and has some implications for gaging. It implies, for example, that upon gaging, when the bushing is seated upon the front reference plane,

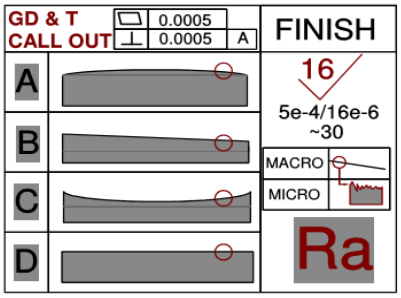

Figure six

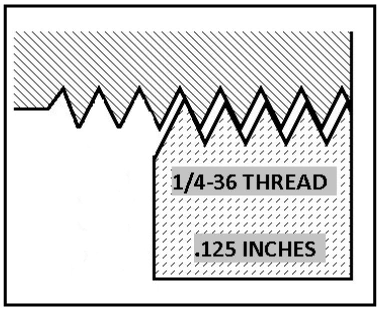

Figure seven

there is potentially a 0.0005 inch variation in the measurement due to the tolerance of the front plane. It further implies that any imperfection in the front plane of the gage's bushing has the potential for changing the gage reading depending on how the gage is seated. It still further implies that rotating the seating of the gage's bushing or a connector's front plane may have an impact on the reading as the lay of the mating planes change.

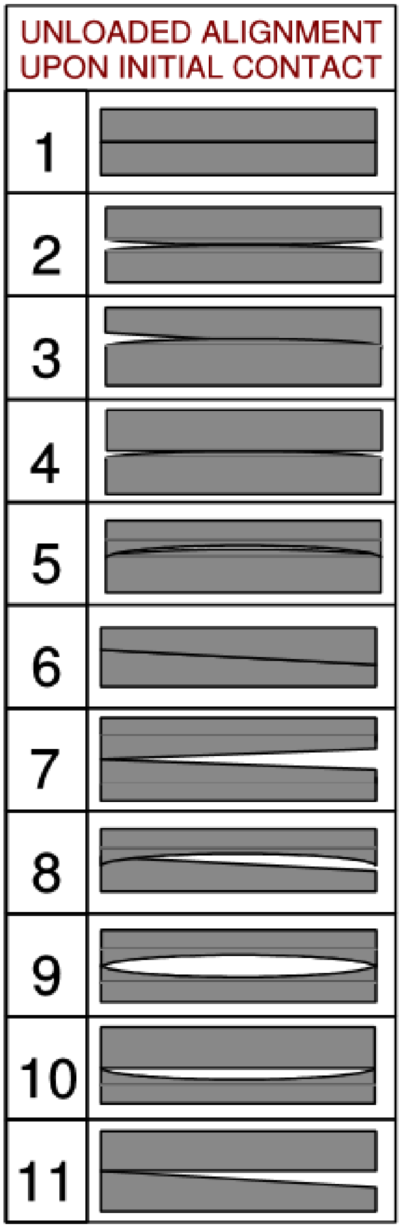

Figure eight

As an aside, also note that the micro finish of Ra16, as called out by 287 (0.0000116 inches) is 30 times smaller than the macro tolerance of the surface. So the Ra, while important for electrical contact and continuity, is a micro condition that should have no impact on gaging and pin depth.

The Impact of Surface Tolerance on Gaging

There are a number of possible surface contours that satisfy the 0.0005 tolerance and the Ra specification. **Figure six** lists the most obvious surface contours, exaggerated for emphasis, that are legal within spec.

The threading for subminiature connectors like 3.5mm and 2.4mm is 1/4-36 and M7x.75, respectively. Note, as pictured in **figure seven,** threading leaves plenty of breathing room to internally realign under load.

The axial force of a subminiature connector upon mating will be given by the expression: **F = T / cD**, where c is the coefficient of friction, D the major diameter of the thread, and T the torque. Hence at 8 in-lbs of torque and a friction coefficient of .2 for steel, the axial force is about 160 lbs. Under load, the solid metal volume of the two mating planes will not deform upon mating due to the nature of the inelastic solid. However, they will tend to realign, attempting to become co-planar – though perhaps not perfectly – under load. Approach orientation in the plane normal to the connector's axis will matter to final seating as well. So there is variability in the 360 horizontal plane (looking into the connector), and there is variability in the vertical approach and final seating angle viewed normal to the long axis of the connector. During mating, the two surfaces may align in a number of ways that can change the location of the pin and socket planes relative to the reference planes. And just as this possibility exists when mating connectors, it is also true that when gaging, the alignment of the bushing and reference plane may also vary depending on how the surfaces are toleranced and how they ultimately align at final engagement.

Figure eight lists a finite number of possible alignments (exaggerated) upon initial contact between either two connectors or between a connector and a gage. **Figure nine** is a sectional view, exaggerated for clarity, illustrating the mating of two planes that are within the IEEE287 GD&T tolerance of 0.0005 for flatness and perpendicularity.

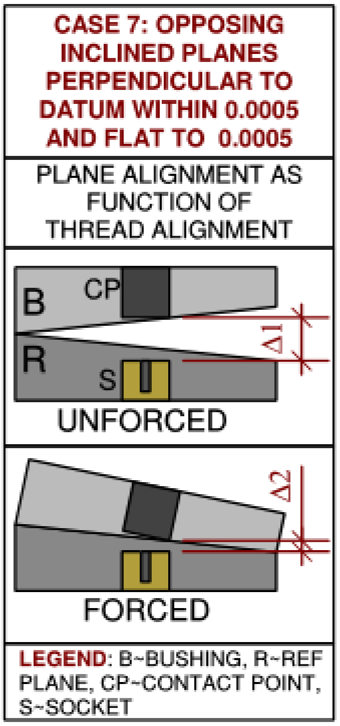

Figure nine

Consider again the three techniques for gaging: threaded, free style and optical: **[i]** If the gaging is ***threaded***, and the alignment is as shown in figure 7, then the forward 160 lb. force will encourage a flush seating and the pin depth will decrease. Given the loose nature of threading prior to final engagement, the surfaces will align by taking the path of least resistance. Hence two inclined planes will tend to become flush under the force of the forward screw action. However, whether this gives optimal recession will depend on where in the 360 degree plane the seating is realized; **[ii]** If the gaging is ***free style***, then the user, seeking minimal recession, will rock bushing B in figure 9 to align with reference plane R, thus allowing the contact point CP to fall (under about 2 ounces of force) on socket S. Again, whether this is optimal, will depend on where in the 360 degree horizontal plane the seating is realized; **[iii]** If the gaging were by non-invasive ***optical*** means, the user would create a virtual plane around the graded plane of the connector, and would calculate recession Δ2 as a function of perfect knowledge of all orientations.

In theory all techniques should produce the same results. However, optical sampling has the edge by removing the observer and literally seeing all possible orientations. This yields knowledge of a best case orientation that could – though not necessarily will – be realized in actual mating. In threaded and free style gaging, they see one sectional slice through two solid volumes. Given 360 degrees of freedom that exist in the horizontal plane, other orientations may produce different results. The art of gaging is to identify the smallest pin depth, and this can only be done by rotating the gage in the horizontal plane to find best case recession. This should be done no matter the gaging technique, the object of gaging being to determine whether the connector is compliant with Standard. With free style gaging, a further requirement – absent the force of threaded gaging – is to rotate and rock the gage to identify best case recession.

The only way to achieve compliance confidence is by sampling the reference plane in a number of different orientations around the horizontal plane, recording the results, and applying commonly accepted uncertainty criteria.

An Example

Consider the gaging of a 1.85mm female connector by two different gages, one threaded, one free style.

Using the threaded gage yields the results in Trial 1 where an attempt was made to ensure little variability in

Keysight Gage 2.4mm Female 11752-60100 Ser 2949A 02220 Master 11752-60004	
1	0.00080
2	0.00080
3	0.00090
4	0.00090
5	0.00085
UNCERTAINTY	
M	0.00085
SE	2.24E-05
U	0.00011
MAX	0.00096
MIN	0.00074
Trial 1	

Keysight Gage 2.4mm Female 11752-60100 Ser 2949A 02220 Master 11752-60004	
1	0.00085
2	0.00075
3	0.00085
4	0.00070
5	0.00090
UNCERTAINTY	
M	0.00081
SE	3.67E-05
U	0.00012
MAX	0.00093
MIN	0.00069
Trial 2	

Mitutoyo Gage 2.4mm Female 543-292B/ID7112EB SN12070726 Flat Master Ra16	
1	0.00080
2	0.00090
3	0.00085
4	0.00090
5	0.00080
UNCERTAINTY	
M	0.00085
SE	2.36E-05
U	0.00011
MAX	0.00096
MIN	0.00074

the applied torque by maintaining an angle with the torque wrench that was normal to the axis of the connector even though ISO6789 allows in calibration a variation of +/-10 degrees off normal angle to the wrench axis.

The first threaded trial is based on five samples realized by rotating the gage to a different position in the horizontal plane before applying a torque of 8 in. lbs. There is a 1/10th peak to peak variation (0.0001) in readings as the gage's bushing samples different conditions within the tolerance window of the reference plane's machined surface. In a second trial, the torque value is increased and decreased for certain readings, yielding smaller recession values.

In this trial, note that under the greater forward force of about 200 lbs from the application of 9 in-lbs of torque, two readings decrease to 70 and 75 tenths. This can be interpreted to mean – not that the solids coming in contact experienced any kind of material deformation – but rather that the asymmetry of the mating plane had created a gap that was closed under greater force, thereby becoming more co-planar.

Gaging the same connector with a free style digital gage based on a Mitutoyo platform with a custom ATX bushing and contact point gives results similar to the first trial with the threaded gage – as illustrated in the third table above.

The values below the tables include the repeatability given as the Standard Error of the Mean. The final uncertainty (U) is based on the RSS sum of the ISO17025 calibration uncertainty and the repeatability, then expanded by a factor of 2 for a second order confidence level of 95% which is consistent with best GUM practice.[3]

Summary

In general, gaging seeks to identify a best estimate of recession, ideally based on a combination of sampling data and uncertainty of the mating of two planes that yields minimal recession. It is this value that is compared to Standard to determine the degree of compliance. The above analysis stresses that hand gaging is inherently fraught with uncertainty, in part due to the very nature of the machine tolerance called out by the connector's interface standard. Hence sampling that interface by making a variety of readings in the horizontal plane is the best way to achieve a level of confidence after uncertainty analysis has also been performed. In essence, both free style and threaded gaging are macro profiling techniques using probing gaging features that match in scale to the features being probed and measured.

It has also been suggested that while optical testing may be inherently superior in terms of its ability to non-invasively characterize the grade differences between a connector's inner and outer conductors by removing the observer, it comes at significant cost. And like manual gaging using dial or digital indicator platforms, it must interpret what it “sees” as a variation in surface contour to achieve an estimate of pin depth.

Still further, it was suggested that threaded and free style gaging should produce similar results. In the former case, the forward force of the threading means, coupled with the loose threading of the mating system, creates a realignment that favors a co-planar seating as illustrated in figure 7. In free style gaging, the tester finds a position of flush coplanar seating by moving the gage's bushing to different points around the horizontal plane. In both cases, it is flush geometric alignment that locates the optimal point of least recession for a given sample, less so the force. Both approaches should be equivalent since little force is required to flushly seat the gage on the surface of an inelastic solid.

An area not covered is whether there exists other means to enhance gaging. Recall the Keysight remark quoted above wherein Keysight indicates that the factory has certain testing means more accurate than manual hand gaging, and these means are both “special” (optical), and “electrical”. While it may not be clear what Keysight specifically does electrically to support a finding of optimal pin depth, it is indeed true – as most bench techs and engineers will attest – that an under torqued connection, whether at the front plane of a connector or at the intersection of a solder ferrule and the connector's back plane, can create inadequate continuity. This in turn leads to a so called suck-out condition that looks similar to the suck-out that results when wave guide modes propagate at the expense of the primary TEM mode. Since bad continuity has a signature that can be measured, it may be possible to marry continuity or conductivity testing with mechanical profiling to achieve a better understanding of pin depth relative to an optimal reference plane orientation that achieves best case continuity.

Another concern not covered is the level of uncertainty associated with *reproducibility*, where the latter is defined as the results by different users or by the same user under different conditions. The hand held gage, re-purposed for a measurement it was never designed for, requires care and diligence. Confidence in results is in great measure a function of care. Gaging is part art, part science. And it is best understood within the context of uncertainty that is characteristic of all measurement – and certainly to a no lessor extent for gaging that is primarily a manual exercise. Potential uncertainty related to reproducibility is not covered above though it may worth considering under certain use conditions.

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In another tech brief the authors discuss best practice with regard to calculating the uncertainty in gaging. Also discussed elsewhere is a technique developed by the authors to use high speed data acquisition coupled with an uncertainty module to capture and interpret recession data in real time to better evaluate compliance.

This work was done by Victor R. Spelman of ATX Labs, Vineyard Haven Massachusetts.

1. OSM, 85133-90017: Keysight 85133E/F/H NMD-2.4 mm -f- to 2.4 mm and Flexible Test Port Return Cables, p.3-5ff.

2. November 12, 2016: Case ID 8282229173: Gaging Accuracy, Keysight IAE.

3. Evaluation of measurement data – An introduction to the "Guide to the expression of uncertainty in measurement", JCGM 104:2009