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Quantifying Acoustic Measurement Tolerances and their Importance in the Loudspeaker Supply Chain

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ABSTRACT

Tolerances are attached to any type of measurement and acoustical measurements are typically associated with relatively large tolerances. Despite this, measurement results are often quoted to a high degree of precision and test limits are regularly set without consideration of the measurement tolerances involved. Quantifying measurement tolerances in manufacturing in general is well documented; however the literature fails to describe the application of suitable analysis methods to the field of acoustical measurements. The paper presents the consequences of the presence of measurement tolerances in classifying parts and also describes the shortfalls of the Gauge R&R study. How to quantify a capable measurement system is described including a simple method for quantifying acoustical measurement tolerances. This is particularly relevant in quality assurance in loudspeaker production and relates strongly to the definition of test limits and loudspeaker specifications in the supply chain.

1. INTRODUCTION

In almost any manufacturing process, quality assurance in the supply chain (the journey of a part from raw materials to customer product) is guaranteed through the use of gauges. In other words, produced parts are measured against the part specification using some kind of measuring equipment or gauge. A gauge may, for example, be a calliper, thermometer or weighing scale. In acoustics and especially loudspeaker production, we attempt to ensure quality assurance through testing of parameters such as sensitivity, frequency response, distortion and rub and buzz. Quality is likely to be checked at several places along the supply chain. In the context of loudspeaker drive units and a loudspeaker system supply chain, quality control is often performed in three places;

- End Of Line (EOL) testing at the drive unit manufacturer.
- Incoming Quality Control (IQC) inspection on arrival at the loudspeaker system manufacturer.
- EOL testing of the assembled product.

The overall performance of loudspeaker systems largely hinges around the performance of the individual drive units and therefore quality control also hinges around the drive unit specifications. To avoid too many headaches in the real world, it is necessary that the supplier and manufacturer define exactly how they implement their individual quality control gates. Furthermore, it is paramount that the gauge in such quality control steps is capable of performing the measurements desired. This means that the equipment can reliably test the parameter of interest to an appropriate degree of precision compared to the desired specification or approval window. *For example, a ruler with 1cm divisions cannot be used to verify the length of bolts with a 34+/-1mm specification.* The performance of a measuring system is often verified with a Measurement System Analysis (MSA) which aims to describe the tolerances of the gauge and thus the appropriateness of the gauge to the task in hand.

The motivation behind this paper has been the author's experience in the loudspeaker industry and in quality assurance with the general observations that;

- Well-known quality methodology and guidelines from the manufacturing industry as a whole are not entirely valid for acoustical measurements.
- Well-known Gauge R&R methodology is flawed.
- How to apply appropriate quality methodology to acoustical measurements is not described in the literature.
- Manufacturers in the loudspeaker industry have widely varying quality performance.
- Manufacturers are often unaware of the performance of their gauges but rely on 100% testing anyway.
- Approval (test) limits through the supply chain are generally not aligned and conflicts arise.

Some papers [1] have touched on the subject but have failed to dig into the details of the Gauge R&R, standard quality methodology and inappropriate guidelines. It is the author's ambition that this paper can shed some light on the issues above and hopefully aid understanding and future alignment of methods.

2. THE CONCEPT AND CONSEQUENCIES OF MEASUREMENT TOLERANCE

For complete understanding, this section will describe the concept of measurement tolerance and the consequences hereof. The information presented here and figures 1 to 4 have been inspired by Wheeler [2]. Consider figure 1 that illustrates a fictional perfect gauge. This gauge will give you the exact and same value of the part every time.

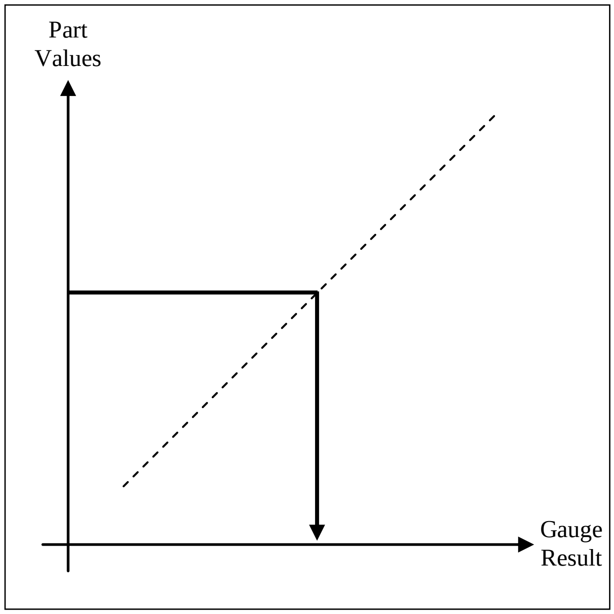

Figure 1 A perfect gauge

In practice though, any real gauge has a tolerance associated with it as illustrated in figure 2.

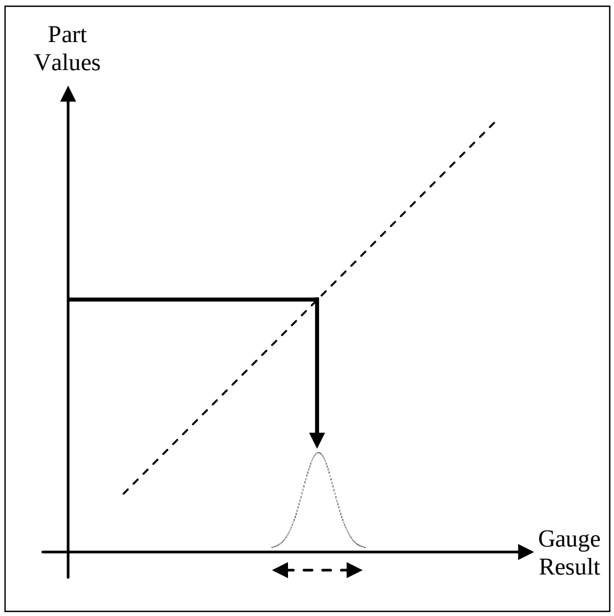

Figure 2 A real gauge with a certain tolerance

Consequently, measuring parts in the presence of measurement tolerance will result in varying results for the same part with repeated measurements. Our aim therefore is to ensure that this measurement tolerance is appropriately small so that we get a reliable or trustworthy picture of the performance of the part.

Naturally, there will also be a spread in performance of parts from the manufacturing process due to a variation in raw materials and assembly processes. In loudspeaker production this is reflected in varying sensitivity for example. Figure 3 illustrates the fact that parts are produced with a spread of values and tested with a real gauge with a certain measurement tolerance.

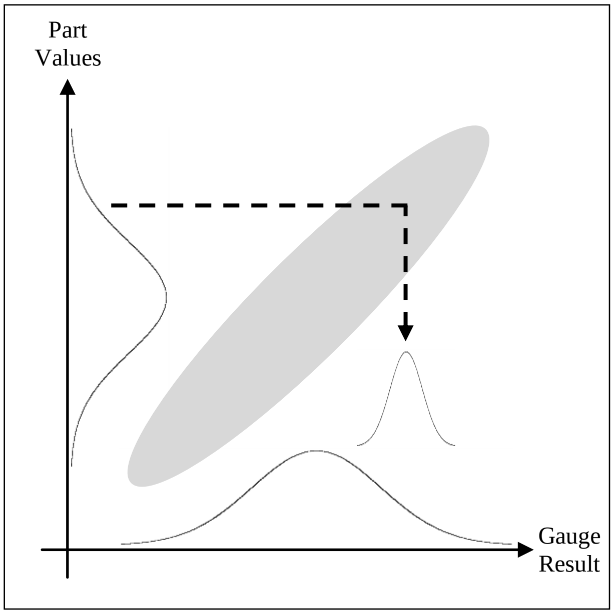

Figure 3 Spread of production parts and a real gauge

The figure above illustrates a *bivariate process* in which the outcome is the result of two individual processes, each with their own variance. It follows that measuring a population of parts with a gauge will result in a larger variance of data than the original parts possessed. Of course, a more precise gauge will minimize this extra variance caused by measuring.

Figure 4 further extends the illustration to include specification limits that distinguish between good/conforming parts (OK parts) and bad/non-conforming parts (Not-OK or NOK parts). Limits are commonly referred to Upper and Lower Specification Limits (USL and LSL respectively).

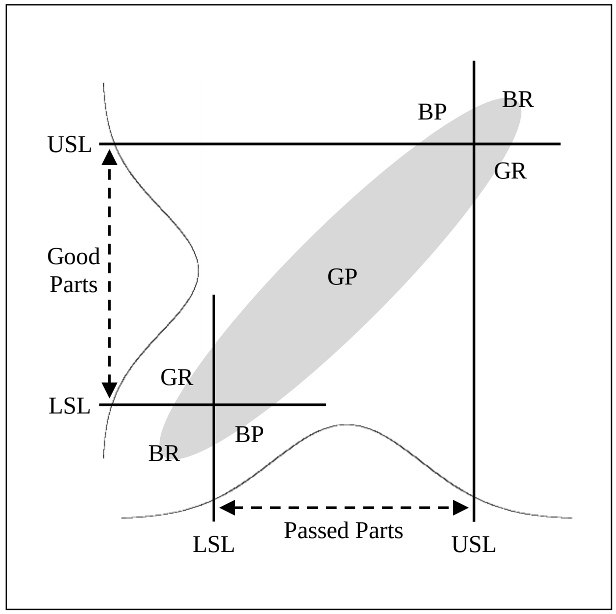

Figure 4 Resulting classifications of parts with specification limits and a real gauge

This figure above demonstrates that two new classifications of parts arise due to the presence of measurement tolerance. The four classifications are;

- GP: good or OK parts that are passed ☺
- GR: good or OK parts that are rejected ☹
- BR: bad or NOK parts that are rejected ☺
- BP: bad or NOK parts that are passed ☹

This can be explained by considering an example of a part, which is 0.2dB outside the USL for sensitivity (a NOK part), but is deemed OK due to the fact that the measurement system has a tolerance of +/-0.4dB.

NOK parts deemed OK are often called ***missed faults***, and OK parts deemed NOK are often called ***false failures***. It is very important to note, that these parts can switch classifications between supplier EOL and customer IQC testing if the two quality assurance gates test against *the same* test limits (because there is as a measurement tolerance present in both gauges). This is unfortunately often the case in a loudspeaker supply chain and is illustrated in figure 5.

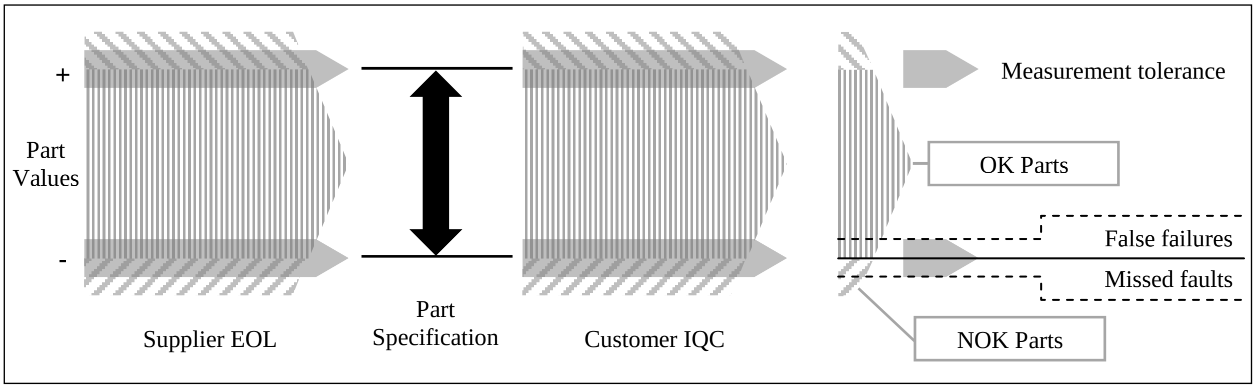

Figure 5 A typical supply chain with the same test limits at supplier EOL test and customer IQC test

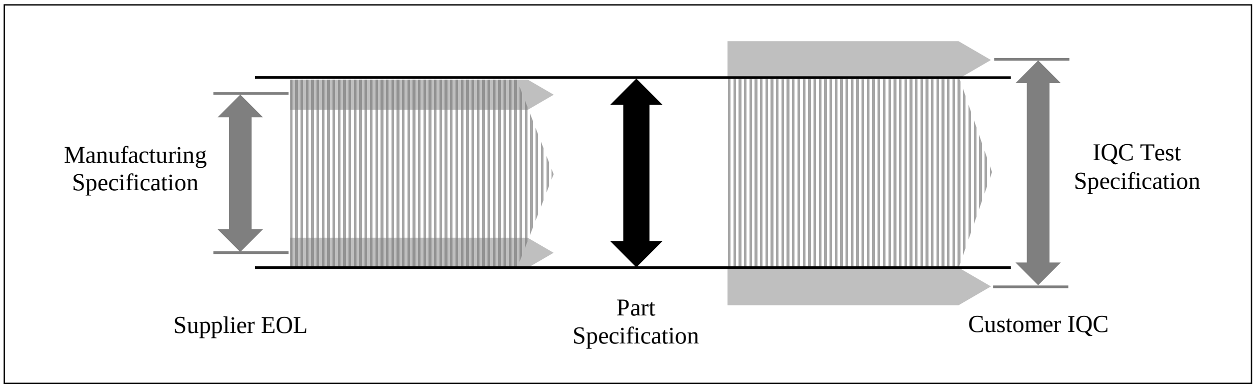

Figure 6 A supply chain aligned to avoid false failures and missed faults

Clearly, when seen in a supply chain or commercial sense, the presence of these unwanted classifications costs time and money and are regularly an issue quality-responsible people in the industry have to deal with.

2.1. A Strategy to Remove Wrong Classifications in the Supply Chain

Firstly, we must consider the purpose of the individual quality assurance gates mentioned above:

- The purpose of the supplier EOL quality assurance is to prove that parts are within specification such that only OK parts are shipped to the customer.

- The purpose of the customer IQC quality assurance is to prove parts are out of specification or NOK.

Of course, it is not *a goal* of the IQC test to find out-of-specification parts and in the case of reliably high quality parts (always OK), the IQC test will take the form of spot-checks with lowering frequency with time (the focus will naturally be on parts that regularly cause trouble as there is no reason to spend a lot of time checking good parts).

Figure 6 illustrates a supply chain aligned to avoid the two extra unwanted classifications of parts; false failures and missed faults. This strategy is referred to as applying ***Manufacturing Specifications*** and is described thoroughly by Wheeler [3, 4].

Applying manufacturing specifications means that the supplier **tightens** their EOL limits by the measurement tolerance (at each limit) in order to guarantee that shipped parts are according to specification.

Additionally, the customer **widens** their IQC limits by their measurement tolerance in order to prove that parts are not according to specification. These concepts are further described and standardized in ISO 14253-1 [5].

Consider a realistic example where a particular part specification is +/-3.0dB and where the supplier and customer equipment tolerances are +/-0.3dB and +/-0.5dB respectively. The supplier should then set their EOL test limits to +/-2.7dB and the customer should set their IQC test limits to +/-3.5dB.

It follows that by increasing the amount by which we tighten the test specifications at supplier EOL, or widen the test specifications at customer IQC, will increase the certainty that false failures and missed faults will not appear. However, unlimited tightening or widening of limits cannot occur without due consideration for the production yield (process capability) or the effectiveness of IQC.

Consequently, we must clearly define how to quantify measurement tolerances and therefore derive the amount by which the part specification must be tightened or widened at EOL and IQC respectively. A method for quantifying measurement tolerances relevant for acoustical measurements is described later.

3. QUANTIFYING THE MEASUREMENT SYSTEM

Quantifying the capability of the measurement system via its tolerances is essential for many reasons;

- The measurement tolerance will tell us if the measurement system is *capable* or not.
- The measurement tolerance will define the *resolution* of the measurement system.
- The measurement tolerance is needed to apply manufacturing specifications and align the supply chain to avoid false failures and missed faults.
- The method of quantifying measurement tolerances will most likely tell us if there are flaws in the measurement system or in the way the operators use the measurement system.

Without having quantified the tolerances in a measurement system, one is essentially operating blind and one could futilely be performing 100% screening. In some types of acoustic measurements, particularly rub and buzz, the measurement tolerance can be significant and could in fact exceed the window one is testing against thus making testing futile.

3.1. Definition of a Capable Measurement System

Quality methodology and guidelines from the manufacturing industry regularly refer to the Precision-to-Tolerance ratio or P/T ratio as a tool for defining if a measurement system is capable or not. The P/T ratio is commonly defined by:

$$P/T\ ratio = \frac{6\sigma_m}{USL - LSL} \qquad (1)$$

Where σ_m is the standard deviation of the measurement system itself and *USL* and *LSL* are the specification limits. The P/T ratio describes how much the measurement system tolerance “eats up” the limit window. General guidelines in the manufacturing industry, which are also those adopted by the Automotive Industry Action Group (AIAG) [6], use the three categories given in table 1 for classifying the capability of a measurement system.

P/T ratio	Capability
< 0.1	Acceptable
0.1 to 0.3	May be acceptable
> 0.3	Unacceptable

Table 1 Common industry guidelines for P/T ratio

It can be concluded from these commonly used guidelines, that for a measurement system to be acceptable, then for a P/T ratio < 0.1 from (1):

$$\sigma_m < \frac{USL - LSL}{60} \qquad (2)$$

It will be seen that achieving this common guideline is a utopia in most cases, but especially so for acoustical measurements. Indeed several quality experts, including Wheeler [7, 8], question the wisdom of using the P/T ratio to describe the capability of a measurement system, and refer to it as inadequate and inappropriate. In short, this is simply because the P/T ratio is not related to the actual process capability but only the size of the limit window (USL - LSL) and therefore tells us nothing about the measurement system’s ability to track changes in the process – or how suitable the measurement system is for measuring the process in hand. Wheeler [8, 9] describes thoroughly how the ***Intraclass Correlation Coefficient*** or ICC is a more suitable determinant of how capable a measurement system is. The ICC is given by:

$$ICC = 1 - \frac{\sigma_m^2}{\sigma_x^2} \tag{3}$$

Where σ_m is the standard deviation of the measurement system itself and σ_x is the standard deviation of the measured parts (total process). It can be seen that as the measurement deviation becomes small relative to the process deviation, the ICC approaches 1. Logic also tells us that as our process improves (leading to a higher process capability and smaller σ_x) our measurement system must also be improved to be able to continue to track the process. A large measurement tolerance will naturally smear the part values as illustrated in figure 3. Wheeler [8] proves that for the measurement system to be a ***first class monitor*** of the process (and hence be classed as a capable measurement system) then process signals (trends) are attenuated by less than 10%, or:

$$1 - \sqrt{ICC} \leq 0.1 \tag{4}$$

From (3) and (4):

$$ICC = 1 - \frac{\sigma_m^2}{\sigma_x^2} \geq 0.81 \tag{5}$$

Rearranging:

$$\sigma_m \leq 0.44\sigma_x \tag{6}$$

If we stipulate that the measurement system should be a first class monitor for process capabilities up to 1.5 (which in the author's experience is quite adequate for loudspeaker drive unit supply chains) then in this case a double-sided limit must contain up to 1.5 times $6\sigma_x$ (a process capability of 1 means the limit includes $6\sigma_x$):

$$\sigma_m \leq 0.44\sigma_x = 0.44\frac{(USL - LSL)}{9} \tag{7}$$

$$\sigma_m \leq \approx \frac{USL - LSL}{20} \tag{8}$$

If we define the **measurement system tolerance T_m** to be equal to two standard deviations ($2\sigma_m$), which is equivalent to a 95% confidence interval, then from (8):

$$\pm T_m = 4\sigma_m \leq \frac{USL - LSL}{5} \tag{9}$$

Similarly for a single-sided (upper) limit:

$$+T_m = 2\sigma_m \leq \frac{USL}{5} \tag{10}$$

It can be concluded that for the measurement system to be *capable*, the measurement tolerance T_m must be less than or equal to one-fifth of the limit window.

For example, if a particular loudspeaker specification states a limit window of +/-2.5dB, then the measurement system tolerance T_m must be ≤ +/-0.5dB.

Interestingly, applying equation (8) to the equation for the P/T ratio (1) we find:

$$P/T\ ratio \leq 0.3 \tag{11}$$

In other words, the author strongly recommends that for acoustic measurements in a loudspeaker supply chain, the industry guidelines for the P/T ratio should be simplified to those shown in table 2. This conclusion relaxes the unrealistic guidelines of table 1 to something sensible and certainly realistic.

P/T ratio	Capability
≤ 0.3	Acceptable
> 0.3	Unacceptable

Table 2 Suggested future guidelines for P/T ratio for acoustic measurements in a loudspeaker supply chain.

Furthermore, from the definition that the measurement system tolerance T_m is equal to two standard deviations ($2\sigma_m$), it follows that when manufacturing specifications as described in section 2.1 are applied by tightening the part specification by the supplier EOL measurement system tolerance at each limit for supplier EOL tests, then the supplier can be certain that ***at least* 99%** of the shipped parts will be conforming. This will be true for process capability indexes as low as 0.1 and higher. The certainty of conforming parts increases to 99.7% with process capabilities over 1. The calculations are given in detail by Wheeler [3] and are based on a bivariate model of two normal distributions as introduced in section 2.

Similarly, the limits in the customer IQC tests are defined by widening the part specification by the IQC measurement system tolerance at each limit.

Now we have a guideline for when a measurement system is capable and also how to calculate the test limits in the EOL and IQC quality assurance gates. The next step is to define how to quantify the measurement system tolerances and identify the measurement system tolerance T_m in each measuring system or gauge.

3.2. Quantifying Measurement Tolerances

For many decades, a much-used method of quantifying measurement error in an MSA study has been to use a Gauge R&R study. This method has also been popularized by the AIAG [6]. This method and its shortfalls, and an alternative method which the author believes is more suitable for quantifying acoustic measurement tolerances are presented below.

3.2.1. Gauge R&R Studies

A Gauge R&R study refers to a study that has the aim to quantify the *Repeatability* and *Reproducibility* of a gauge. In other words, quantifying how good a gauge is for repeatedly measuring the same part and how reproducible are the gauge results with different operators. Typically a Gauge R&R study will consist of a number of parts that are each measured a number of times by several operators in the same gauge. The result is a set of data that can be analysed, with the use of *bias correction factors* (!) that have evolved through the history of the Gauge R&R, in order to estimate:

- Repeatability or Equipment Variation, *EV*
- Reproducibility or Appraiser Variation, *AV*
- Combined repeatability and reproducibility or *GRR*, which is an estimate of the measurement system standard deviation σ_m.
- Product Variation, *PV*
- Total Variation, *TV* which is an estimate of the total process standard deviation σ_x.

It can be noted that the total variation is derived by:

$$TV = \sqrt{EV^2 + AV^2 + PV^2} \qquad (12)$$

And:

$$GRR = \sqrt{EV^2 + AV^2} \qquad (13)$$

Each of these descriptors defines the variance of individual distributions and logically their sum is the square root of a sum of squares. However, the Gauge R&R method referred to here unfortunately comes to short when the descriptors calculated are expressed as percentages of the Total Variation for the purpose of evaluating if the gauge is capable or not. For example, a gauge would be defined as *good* (capable) when:

$$\%GRR = 100\frac{GRR}{TV} < 10\% \qquad (14)$$

Furthermore, ratios between 10 and 30% are classed as marginal and ratios greater than 30% are said to be unacceptable. Interestingly, when calculating the percentage contributions for each of the descriptors, it becomes clear that the percentages do not add up to 100%. This error should though be obvious as the values only "add up" if considered as variances as related in equation (12).

This significant shortfall has the consequence that any conclusions drawn from a Gauge R&R study, such as the one described by the AIAG, are likely to be incorrect. Wheeler [10] presents a thorough analysis of the shortfalls of the AIAG Gauge R&R method including noting that the *number of distinct categories* is also not a useful parameter for determining the capability of a measurement system.

3.2.2. Author MSA for Quantifying Acoustic Measurement Tolerances

Our aim is to quantify the measurement tolerance involved in measuring the same part by different operators in order to identify the measurement system tolerance only. Identifying the product variation in loudspeaker production requires a different magnitude of study as noted in section 5. The author has attempted to define an MSA method that is straight-forward and removes the complexity found in many Gauge R&R type studies. The method described here also clearly illustrates how *many* measurement points can be dealt with (a quality assurance gate in a loudspeaker supply chain often involves several hundred data points divided across various measurement types and frequencies). The author MSA method is described step-by-step below:

1. A test jig is manufactured for the specific loudspeaker drive unit and test box or chamber in question. The test jig typically includes a dedicated test baffle for the drive unit, a rear volume if necessary and dedicated electrical contacts.

2. The DUT shall be an acclimatised [11] Golden Device (reference unit) or other nominal unit.

3. The measurement system is programmed to measure the relevant part specifications (such as sensitivity and frequency response). Programming test limits is not necessary for the purpose of the MSA as the measurements are performed with a nominal device. Note that the measurement system should record data to a precision of 1/100th of a unit for the recorded precision of the data to be related fairly to the measurement tolerances expected in capable acoustic measurements (see section 3.3).

4. Operator 1 mounts the test jig for the specific drive unit in the test equipment and then performs 10 measurements of the DUT. The DUT is disconnected and removed from the test jig between each measurement. On completion of the 10 measurements, the DUT *and* test jig are removed from the test equipment.

5. Operators 2 and 3 repeat step 4 above, performing measurements 11 to 20 and 21 to 30. If only two operators are available, then they can each perform 15 measurements. All measurements must be made within a short time, such as less than 1 hour, so ambient atmospheric changes are minimised [11].

6. The 30 measurement sets are recorded for statistical analysis such as text files that can be processed in a Microsoft Excel spreadsheet for example. For **each measurement type** and **each frequency point**, the *intermediate* measurement tolerance t_m is calculated from the sample standard deviation using:

$$t_m = 2\sigma_m = 2\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \mu\right)^2} \qquad (15)$$

   The sample size n in this case is 30 and μ is the sample mean value. Whether using the *sample standard deviation* or *population standard deviation* has very little significance on the result. Note that the values calculated are in the same units as the measurement data. At this point in the MSA, we have values of t_m at each test frequency point for each measurement type.

   In reality, it is not practical to use a different tolerance value for each test frequency point; therefore the measurement tolerances should assume a single value T_m in appropriate frequency ranges. This single value should enclose the envelope of the individual tolerance values in the given frequency range (such that the largest tolerance t_m found in the frequency range of interest is simply rounded up to one decimal place). This is illustrated in figure 7, where the measurement tolerance T_m is determined in two frequency bands according to the part specification (in this example the data is 1/6th octave with two bands 100 to 400Hz and 400 to 1000Hz).

7. The MSA can be approved for **each measurement type**, if the measurement tolerance T_m obeys the requirement for double-sided limits, in each frequency range or band, from equation (9), that:

$$T_m \le \frac{USL - LSL}{10} \qquad (16)$$

   Similarly for single-sided (upper) limits, in each frequency range or band, from equation (10) that:

$$T_m \le \frac{USL}{5} \qquad (17)$$

   In the case of a sensitivity measurement, there will be a single figure result and also only a single tolerance value for this measurement type.

8. Capable (approved) measurement tolerances are implemented in the supply chain as described in section 2.1. Should the MSA reveal incapable measurement tolerance values, then the flow chart illustrated in figure 8 should be followed.

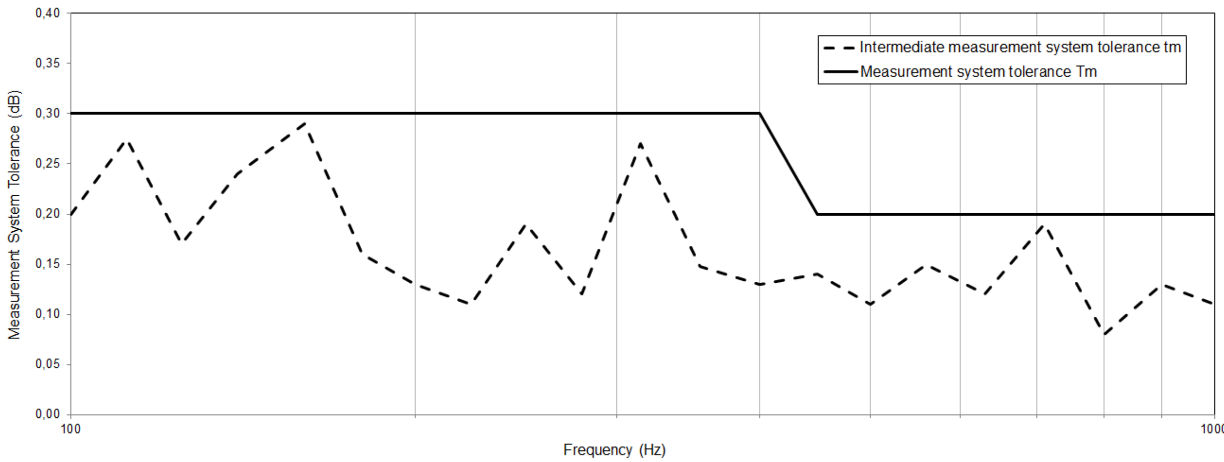

Figure 7 Illustration of how measurement system tolerances can be given single values across frequency ranges

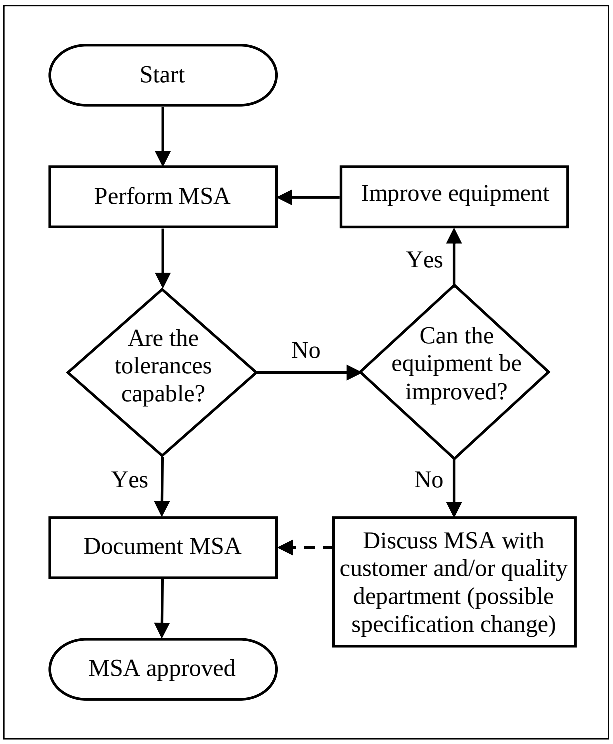

Figure 8 MSA decision flow chart

In the case of incapable tolerance values, the consistency of the operators can be investigated. This can be done simply by applying equation (15) to each of the three sets of operator measurements and comparing the resulting values for the intermediate measurement tolerance. If an operator “sticks out”, they may not be trained in the correct use of the equipment or jigs. Should improvements made to the equipment still not lead to an approved MSA, then averaging multiple measurements can be considered as a strategy to reduce measurement tolerances further. A final consequence of a poor MSA result can be that the test limits originally desired cannot be achieved and that the supplier and customer may have to agree on a new part specification or accept a lower production capability (yield) with the possible consequence of a part-price increase.

3.3. A Note on Data Resolution

As the measurement increment increases (resolution decreases - fewer decimals in a digital system), the error in reading the correct value of a part also increases. On the other hand, decreasing the measurement increment (increasing resolution – higher bit depth, more decimals in a digital system) does not increase the precision of the measuring system beyond the measurement tolerance. Therefore, recording many decimals smaller than the measurement tolerance is pointless and in fact leads to a false sense of precision. Wheeler [3] derives that the measurement increment or resolution need not be smaller than approximately $0.14\sigma_m$ (0.2 probable errors). From table 3 listing capable measurement tolerances, we can conclude that it only makes sense to record data in acoustic measurements to one one-hundredth ($1/100^{th}$) of a unit.

3.4. Typical Reasons for Poor MSA Results

The following points illustrate typical reasons for poor MSA results and incapable measurement tolerances:

- Poor signal-to-noise ratio in the measurements.
- Poor programming of the test sequence (wrong signal level, signal duration, delay etc.).
- Large positioning tolerances of the jig and/or DUT.
- Single “bad” frequency points caused by resonances or reflections in the test box.
- Poor electrical contacts.
- Lack of operator training.

When working with qualifying measurement equipment for a given quality assurance task and thus performing MSA studies and quantifying the measurement system tolerances, the valuable nature of such studies quickly becomes clear. In fact, the MSA should identify problems or shortcomings in the test equipment and experienced personnel will quickly be able to recognise root causes and improve poor measurement equipment.

3.5. Capable Measurement Tolerances

The table below lists acoustic measurement tolerances achievable in high quality measurement systems in the context of a loudspeaker supply chain. The values are guidelines only and are to illustrate what is possible in high-performing measurement systems.

Measurement Type	Capable Tolerance T_m
Sensitivity	< +/-0.2dB
Frequency Response	< +/-0.5dB
Impedance	< +/-0.2Ω
Distortion (THD)	< +1dB / < +0.4pp*
Rub & Buzz	< +2dB

Table 3 Capable acoustic measurement tolerances

*pp means percentage points in the case where distortion is measured absolutely in percent.

Measurements like distortion and rub and buzz usually only have single sided upper limits, hence the tolerance is only indicated as a +. It is the authors experience that measurement tolerances in rub and buzz measurements are by far the most difficult to tame and can be surprisingly large (of the order of 4 to 12dB depending on the jig and rub and buzz algorithm). It is also mostly in these cases where 100% screening can be futile.

From equations (16) and (17) it follows that the smallest measurement tolerances achievable in high quality measurement systems will dictate how narrow part specifications can be. For example, a frequency response tolerance of +/-0.3dB dictates that the narrowest frequency response limit window may be +/-1.5dB. On the other hand, wider part specifications also relax the requirements made on the measurement system. For example, a limit requirement of +/-5dB only requires a measurement tolerance of +/-1dB.

4. EXAMPLES OF MSA RESULTS

This section gives some real life EOL and IQC examples of using the author MSA method described in section 3.2.2.

4.1. Frequency Response

Figure 9 shows the 30 measurements from 3 operators each performing 10 measurements of the same 100mm midrange unit. The measurements where performed in an IQC test box with a stepped sine stimulus at $1/12^{th}$ octave resolution and $2.0V_{rms}$. It becomes immediately clear that the variation between measurements is very small despite the part and jig being mounted and dismounted as instructed. This is one of the strong points of performing the MSA – visually, the 30 measurements show if something is wrong.

It is interesting to note that the dip in the response of the midrange at 2800Hz is caused by the driver and not by a problem in the measurement set-up – and therefore does not lead to a larger tolerance at this frequency.

Figure 10 shows the resulting intermediate measurement tolerance t_m and the final measurement system tolerance T_m which is +/-0.2dB in the whole frequency range. This tolerance approaches the limit of what is possible in a production test box and is a capable tolerance for limits as tight as +/-1.0dB, although the actual limits for the loudspeaker in question where wider.

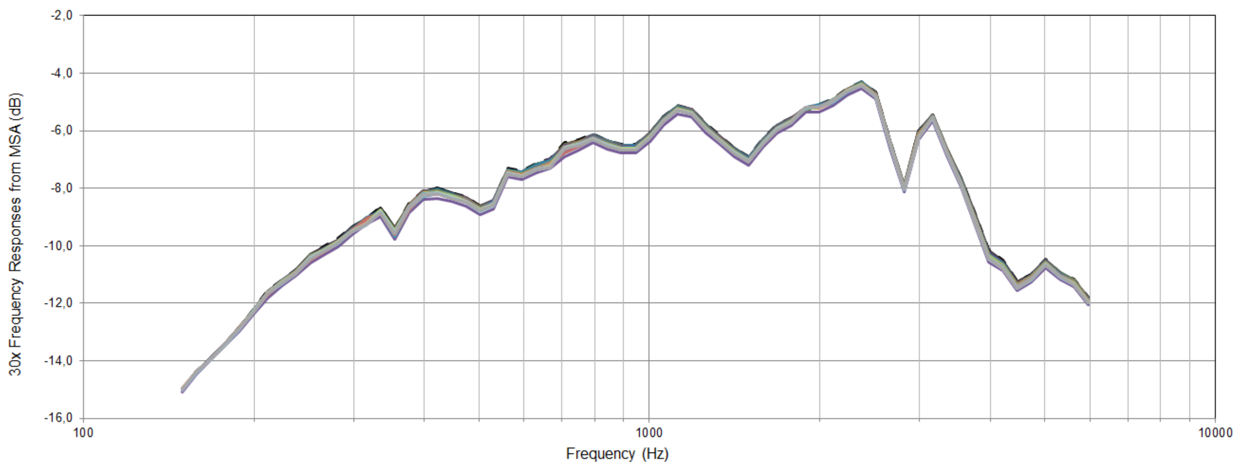

Figure 9 MSA frequency response measurements of a 100mm midrange

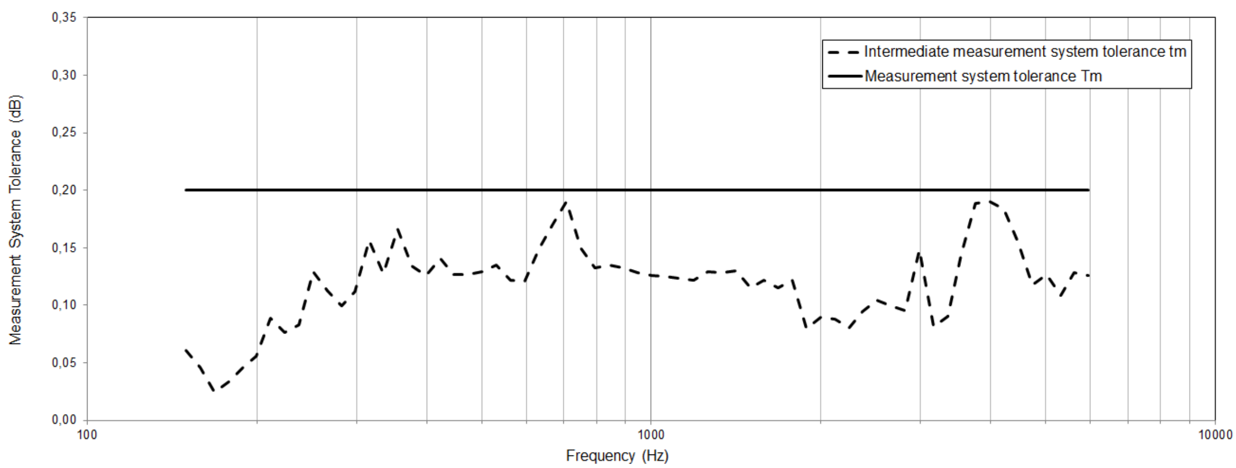

Figure 10 Measurement tolerances calculated from the 30 MSA measurements in figure 9

4.2. Total Harmonic Distortion (THD)

Figure 11 shows 30 MSA measurements of THD (2^{nd} to 5^{th} harmonics) of a nominal 19mm tweeter unit. The measurements where performed in an EOL production test box with a stepped sine stimulus at $1/24^{th}$ octave resolution and 2.8V_{rms}. It can be seen that there is more variation at low and high frequencies. Figure 12 shows the resulting measurement tolerances where the final measurement tolerance T_m is set in two frequency bands (+1.1dB at 1000 to 2000Hz and +0.7dB from 2060Hz to 6000Hz). The relative EOL limits must therefore be at least +5.5dB and +3.5dB respectively above the reference. Following the MSA, the final test configuration was chosen to stop at 6000Hz as the measurement runs into the noise floor above this frequency.

4.3. Rub and Buzz

Figure 13 shows 30 MSA measurements of rub and buzz of an 80mm midrange unit. The measurements where performed in an EOL production test box with a stepped sine stimulus at $1/6^{th}$ octave resolution and 5.7V_{rms} using a simple 5^{th} harmonic 8^{th} order high-pass tracking filter.

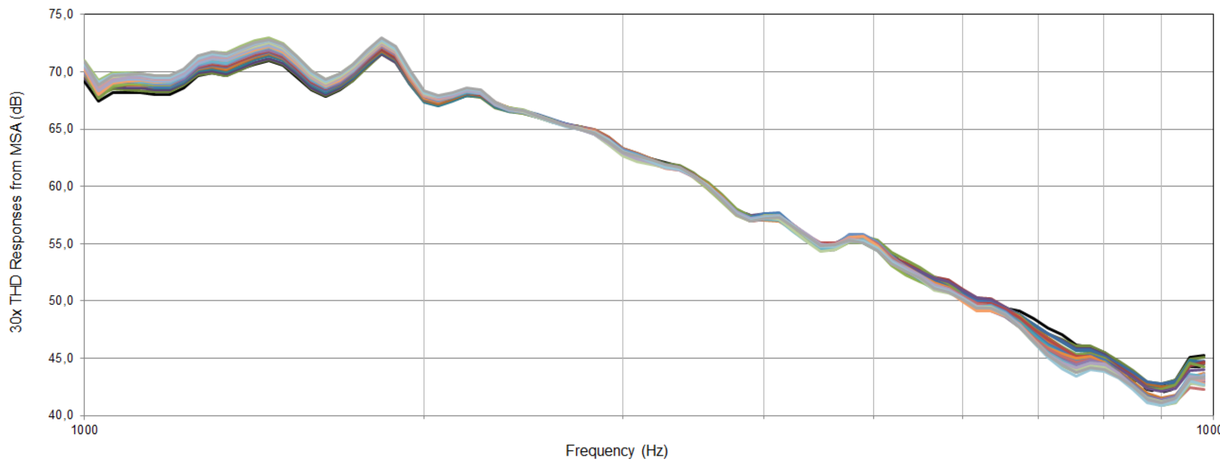

Figure 11 MSA total harmonic distortion measurements of a 19mm tweeter

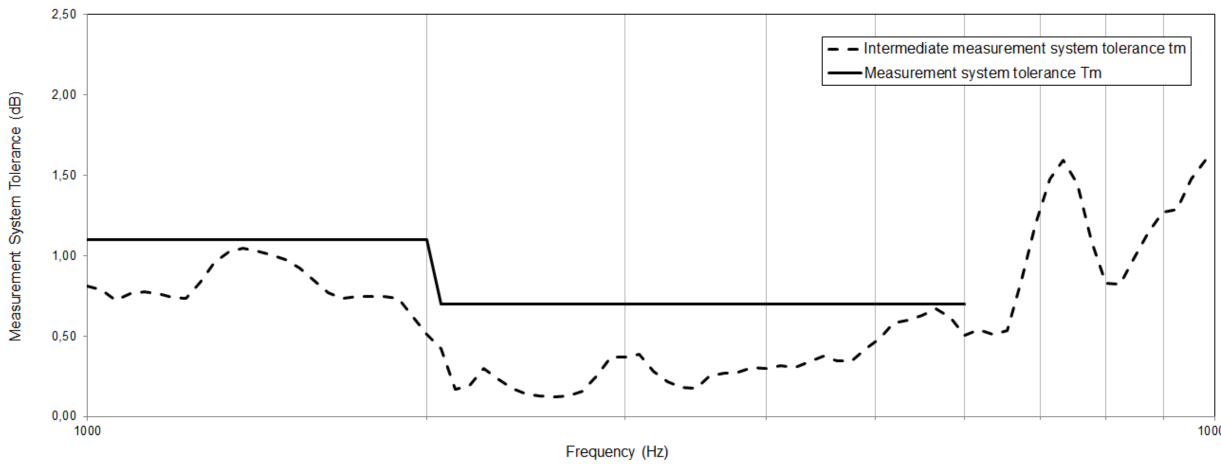

Figure 12 Measurement tolerances calculated from the 30 MSA measurements in figure 11

It can be seen that there is a great deal of variation in most of the frequency range. Figure 14 shows the resulting measurement tolerances where the final measurement tolerance T_m is set in the whole frequency range to +3dB. The relative EOL test limit must therefore be at least +15dB above the reference for this to be classed as a capable measurement system for testing rub and buzz!

This example has been included here to illustrate the challenge with rub and buzz measurements, as in reality the system is measuring its own noise floor when there is no rub and buzz from the loudspeaker drive unit. This sensitivity to noise should of course be reduced with more modern *almost intelligent* rub and buzz algorithms, and is the subject of ongoing study.

5. PROCESS CAPABILITY IN LOUDSPEAKER DRIVE UNIT PRODUCTION

The process capability index is a simple way of describing how good a process is at producing parts within the specifications. The value of Capability Index C_p is referenced to a value of 1 describing a process where 6 standard deviations of a normal distribution are between the USL and LSL.

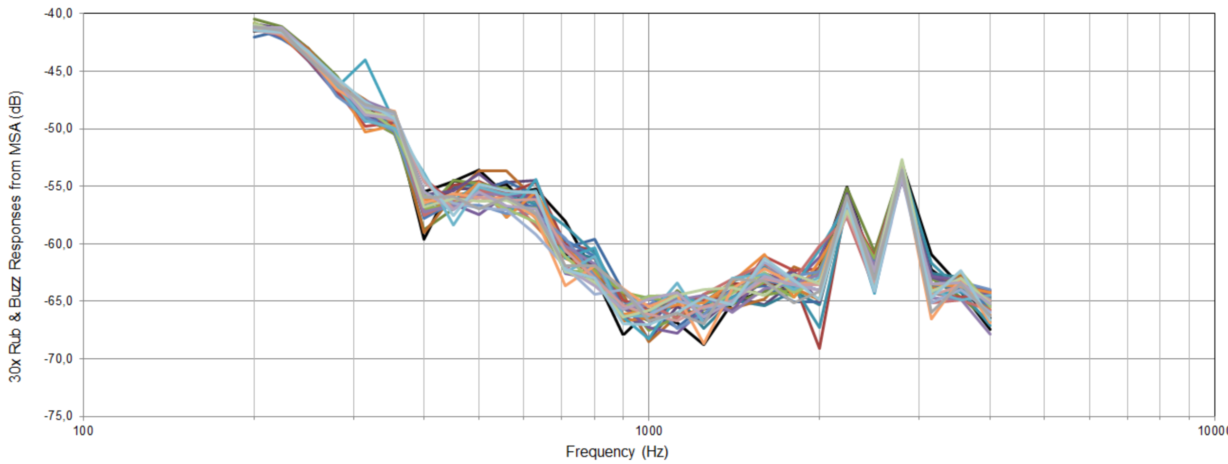

Figure 13 MSA rub and buzz measurements of an 80mm midrange

Figure 14 Measurement tolerances calculated from the 30 MSA measurements in figure 13

A process capability index of 1 should then give a yield of 99.73% for a normally distributed process that is symmetrical about the middle of the limits.

It should also be noted that process capability indices are a function of the specification limits and are therefore only as good as the part specification itself. Obviously, high process capability can be achieved with wide limits. Various branches of the manufacturing industry have developed guidelines for what are acceptable or target process capabilities. Generally, the following values are widely accepted for non-safety-critical processes:

Process	Target Capability Index C_p	
	Double Sided Limits	Single Sided Limits
Existing	1.33	1.25
New	1.50	1.45

Table 4 Standard target process capability values

In quality assurance gates in a loudspeaker supply chain, passing the gate typically involves that 100 to 200 individual measurement points are passed. These measurement points are divided between several measurement types each with a certain frequency range and resolution. It follows logically, that in order for an EOL quality assurance gate in loudspeaker production to fulfil the target process capability values in table 4, then the capability of each individual measurement point must be *significantly* higher than the overall process capability. To put things in perspective, a process capability value of 1.67 means a failure rate of 1 in 1.7 million!

In the author's experience, a good loudspeaker production process with a capable measurement system will achieve the guidelines in table 4 for existing processes *at each individual measurement point*. The resulting overall process should then have a process capability index in the range 0.67 to 1 giving a yield of between 95 and 99.7%. However, the author has also experienced loudspeaker production processes where the capability index is in the region of 0.5 with production yields of only 80%.

Determining the process variation and hence capability index requires some effort in order to get a reliable result. Also, increasingly high process capabilities require an increasing number of parts with which to make the calculation. A simple estimation of the process capability can be made though from the overall production yield (percentage OK parts) and looking up the capability index. However, this tells you nothing about the cause of a low yield and low capability index.

In the author's experience, a robust and useful method is to record measurement data from 100 parts from the first three consecutive production batches (300 parts in total). The full data can then be analysed in a spreadsheet in order to calculate the capability index values at each measurement point. The target should be the values stated in table 4. This method has the great advantage that it provides a good picture of process capability and directs you to the "weak spots" such as too narrow limits in a certain measurement type – or a poor process, where the data is invaluable in a root cause analysis.

Additionally, if the 300 parts where individually numbered, the data can simultaneously be used for selection of nominal parts to become Golden Devices or reference units.

6. CONCLUSION

It has been the aim of the paper to lift the lid on some common misconceptions regarding measurement tolerances in acoustic measurements and highlight some of the shortcomings of standard manufacturing industry guidelines and methods. Furthermore, it is hoped the following points are illuminated:

- All measurement systems have a tolerance associated with them.
- Until an MSA has been performed, one should not assume the capability of the measurement system.
- The presence of measurement tolerances leads to false classifications of parts.
- False classifications can effectively be removed from the supply chain by using *manufacturing specifications* where the supply chain quality assurance gates are aligned using knowledge of the measurement tolerances present.
- Large tolerances compared to the test limits make 100% screening futile.
- Measurement systems with a high data resolution can give the impression of high precision; however it is the measurement tolerance that defines the effective resolution of the system.
- Loudspeaker drive unit production in general struggles to live up to standard manufacturing guidelines for process capability and EOL testing can be called "sorting for quality". Expressed in another way, if we knew the parts we were producing had a very high process capability, there would be no need to test them!

The paper has presented a method for quantifying acoustic measurement tolerances and it is hoped that the paper will lead to further discussion, as the author is aware that different people in the industry are attempting to qualify their measurement systems in some or other way, but are often misguided by standard manufacturing guidelines and quality methods such as the Gauge R&R study.

In summary, the alignment of part specifications requires a capable measurement system and analysis of the process capability so both the supplier and customer can be satisfied. Openness in the alignment phase will lead to more parts within specification, fewer discussions about falsely classified parts and less scrap due to too over-ambitious specification limits or a poor measurement system.

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