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Don't Throw the Loudspeaker Out with the Bathwater! Two Case Studies Regarding End-of-Line Tests in the Automotive Loudspeaker Industry

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ABSTRACT

Mass production of loudspeakers drivers for the automotive market is subjected to the strong requirements dictated by the implementation of the sector Quality System and is heavily conditioned by the low profit margin of what is seen (and actually is) a commodity as many other components of a vehicle; but, differently from other components, a loudspeaker is a complex system made of parts whose performance depends on many factors, including ambient conditions. For these reasons it is quite difficult to impose tight tolerances on loudspeakers and a fair agreement must be found between suppliers and customers to avoid scraping samples that are fine under any aspect, especially considering that the final judgement mainly stays, although not exclusively, in the ears of the end user. In this work two case studies will be presented to show how tolerances could be fixed reasonably.

1 Introduction

Suppliers of loudspeakers drivers - in the following shortened to loudspeaker or driver - for the automotive sector are part of a Quality Management System that started from ISO 9001 and similar requirements, like ISO 10011 and EN 45012, to expand into a more focused standard, the very well-known ISO/TS 16949 recently morphed into IATF 16949:2016. Being part of such an environment poses strong requests in terms of the requirements adopted for products delivery, where the so-called “zero defects” concept is often adopted in quite a literal way; also costs are of paramount importance for both sides of the business, especially for suppliers that are often selling goods with very narrow profit margins. In such a quite competitive market it becomes easily understandable that any small loss of money may have catastrophic consequences, and so any process must be optimized and brought to the highest level of efficiency: under this respect it is quite important to limit the scrap rate of produced parts to the lowest possible value, considering the contrasting requirements of loudspeaker and car manufacturers: the latter requires ideally identical parts so that each car will sound like the others and, very important, to the one that was “frozen” with the approved system audio tuning. The former has to deal with a product that is made of different materials that are heavily influenced by ambient conditions, whose behavior is linear only in a limited range of input signal, and whose output is depending on the input signal itself: all these conditions naturally lead to production tolerance values that should be reasonably liberal, a request that is clearly in contrast with the one expressed by car manufacturers.

We must also consider that any measurement requires time and that modern automatic production lines work in terms of seconds not minutes, so also the number of measurements must be restricted to the really necessary ones, the ones that will separate the good parts from the bad ones without introducing

unnecessary detailed information on the examined samples.
Having seen that it is not realistic to use very tight tolerances along the production line and that the number of measurements must be limited to the few truly essential ones, we will have four possible situations:

1. A good part is approved and shipped to the customer
2. A bad part is rejected
3. A good part is rejected (false failure)
4. A bad part is approved and shipped to the customer (missed faults)

Of the four possible situations, 1. and 2. are fine, 3. is a disaster for the supplier, 4. is a disaster for both the supplier and the customer, so every care must be exercised to avoid the two last situations. Main object of this work is situation 3. that may arise from:

1. Unrealistically strict tolerances
2. Wrong selection of measurements to be done

In both situations a fair agreement must be find between car and loudspeaker manufacturers and we will present two case studies to show how tolerances can be determined using statistical analysis of large batches of data and some notions of psychoacoustics and why even an otherwise important parameter (total quality factor, Q_{TS}) must not be necessarily measured during the final check of production samples, the so called End of Line (EoL) test.

2 Measurements for Loudspeaker Production

Car manufacturers have a tendency to assume that tolerances should not change from those reported in the technical documentation accompanying the offer request to the supplier, to those employed in the production phase, another reason why requested tolerances tend to be very strict. This requirement is not realistic for a series of reasons that are indicated here in the following:

1. Samples used during the design phase are quite limited in number and their components are derived from small, homogeneous lots, so that their characteristics will be quite uniform.
2. The same samples are measured in very well controlled sites, where ambient conditions are quite stable and repeatable and ambient noise is kept at a minimum.
3. Measurements are done at a sufficiently large distance and inside qualified anechoic chambers where even the smallest sources of distortion at 70-80 dB less than the fundamental may be appreciated.
4. Samples are always subjected to thermal stabilization cycles, so that all glued junctions are perfectly polymerized, and they are also subjected to run-in cycles, so that also their mechanical properties are stabilized and will not change appreciably anymore.

Of all the four conditions stated not a single one can be easily guaranteed for mass production samples:

1. For the automotive sector, loudspeaker production batches maybe very numerous and are usually made using components coming from different batches and even different suppliers. It must be added that the same supplier may have different production sites in different countries, and it is not possible to have a perfectly homogeneous production among them.
2. Climatic conditions along the production line cannot be stabilized, and so material characteristics and even electrical quantities (e.g. the DC resistance of voice coils) will vary with seasons and even with days. Also, noise levels along a production line may be quite high, in the range of 80 dB [1], and it must be properly dealt with.
3. Measurements must be done in the near field due to the limited dimensions of test boxes and to increase the S/N ratio: however, working close to the source will decrease the high frequency measurement repeatability and any small positioning errors will lead, in general, to large variations in the measured frequency response.
4. Samples are measured after glue has cured but they will not go through any thermal or mechanical stabilizing cycle, because of production tight times.

As a consequence, production samples will always show a much greater variance than pre-series ones used for design purposes and for this reasons it is not realistic to apply the same tolerances in these two very different situations. Also, since almost 50 years ago it has been recognized that design and production requirements cannot be the same [2]: in 1970 Schroeder indicated the following measurements as those required during the design phase of a loudspeaker system:

1. Frequency response
2. Transient response
3. Distortion
4. Efficiency (and power handling)
5. Directional characteristics
6. Electrical impedance
7. Phase distortion

The same system had to be checked during the final test before delivering by just this different and more limited set of measurements:

1. Frequency response
2. Output level (average SPL)
3. Driver (and system) resonance
4. Manual test by swept sinusoid (looking for Rub & Buzz problems)
5. DC resistance of voice coil

More recently the same topic has been dealt with by different authors: Hutt and Fincham [3] state that even parameters that appear to be of fundamental importance (e.g. the driver resonance frequency, f_s) should be loosely checked during production, and the same goes in general for the so-called Thiele-Small parameters [4], [5], at least not on a 100% basis, while a greater importance should be put on other tests:

1. Frequency response
2. Output level (average SPL)
3. Polarity
4. Rub & Buzz

Also Temme and Dobos [1] state that it is important to perform only those test that can clearly and efficiently (i.e. in a short time) identify scrap parts, and their list of preferred tests include the following:

1. Frequency response
2. Output level (average SPL)
3. Polarity
4. Total Harmonic Distortion
5. Rub & Buzz (including loose particles)
6. Impedance

On the other side, they suggest that the following measurements should not be done at the final assessment of products:

1. Voice coil offset
2. Thiele-Small parameters

It is quite interesting to note that Rub & Buzz is always present in these lists since 1970 (and surely even before) because the human hear is very sensitive to this type of malfunction [6] and it is easily detectable also by the end user because it is very annoying: Rub & Buzz is thus always included in final tests because it is the test that will surely reveal possible sources of very costly repair once the car is on the street. It must be stressed that test systems greatly evolved from the purely manual ones of the past to the highly sophisticated ones of the present days, capable of automatic signal analysis to detect bouncing particles of the dimension of a salt grain [7].

3 What the End User (Actually) Hears

Proceeding from the conclusions of the last paragraph, and without pretending of being exhaustive, it must also be considered what we actually hear, what is the actual sensitivity of our hearing systems to small variations from one loudspeaker to the next one, being theoretically this the base level of any tolerance that will be imposed on production batches. The topic of "Just Noticeable Difference - JND" in the field of acoustics has been the object of many publications (we just may mention the early work of Miller [8], and then other examples from Zwislocki, [9], Zwicker [10], and Allen [11]) and it can be safely stated that an average listener can detect a change in sound level, or better in loudness, when the signal is altered by about 1 dB (*JND in Loudness*) or a change in pitch if the frequency is shifted by about 1-3 Hz, below 1 kHz, and of about 0.6 % above 1 kHz (*JND in frequency*: for comparison, adjacent keys on a piano differ by about 6% in frequency).
Also the dependence of source location has been investigated in terms of level difference between the channels of stereo systems [12] and a roughly linear relationship has been determined which says that a difference of 0.5 dB will move the apparent source of 1°: this means that a inter channel difference of 15 dB will move the stereo source completely to the left or right apex of the stereo triangle.

If we should take such data as they are, the requirements for EoL (End of Line) tolerances on frequency response should be of this magnitude, i.e. ± 1 dB on the useful frequency range but we must consider that:

1. Experiments that lead to the determination of the JND thresholds have been conducted in laboratories, sometimes even anechoic chambers, listener's head immobilized.
2. Listeners were trained and asked to check for such thresholds, attention was not distracted by other activities.
3. Threshold are greatly dependant on the employed stimulus and experimenters used simple, technical sources, like sinusoids or noise bursts, not music.

Compared to the usual listening situation in a car obvious differences spring out, because drivers cannot exclusively concentrate on program details and they will listen to music or voice messages, not to simpler technical signals, so that subtle differences in reproduced levels will go completely unnoticed. But the most single factor making different a car from a laboratory is the presence of a plethora of noise and distortion sources that will mask and greatly modify the sound as emitted by the audio system loudspeakers.
Cars dimensions vary but for an average mid-size automobile it can be noticed that [13]:

1. Lowest acoustical resonances will occur around 100 Hz, not lower than 45 Hz for a van; below this frequency we have a pressure response region where the pressure is almost uniform in the cabin space and it must be constantly maintained because no reinforcement from reverberation or modal modes will occur.
2. Major modal acoustical resonances will occur in the region 80÷300 Hz, with main contributions around 120÷150 Hz. Above this frequencies and till 1 kHz modal density diminishes and coloration is to be expected with peaks/dips as large as 8 dB.
3. Also mechanical resonances are present in car components and large surface ones, like the roof, will contribute significantly to the perceived signal. Door panels and other parts where loudspeakers are fixed will also vibrate producing high level localized or distributed rattling and buzzing sounds.
4. Large surfaces in cars are made of reflective materials and so interference is a common phenomenon for frequencies above 300÷500 Hz, along with diffraction at higher frequencies, both greatly altering the system frequency response.
5. Noise coming from engine, road, wind will reduce the audio system dynamic range and will greatly mask program perception for signals below about 500 Hz.
6. Ambient conditions have a great influence on loudspeaker performance [14] because materials interact greatly with the environment and change their characteristics accordingly: for example, the f_s of a foam or rubber surround woofer will shift of about 15% for a 0-70 °C range of temperatures, while the frequency response may experiment a level drop of about 2-3 dB in the same conditions.
7. Finally, all above mentioned phenomena are time varying because the listening environment will experiment random short-time modifications (e.g. a window opening) and long-time ones because of mechanical components wear producing vibrating loose joints, degrading surface finishes with changing reflective properties and degrading damping materials.

After these considerations it seems quite unreasonable to stick to ± 0.5-1 dB tolerances for frequency response at the EoL stage because the reproduced signal will be anyhow altered in such a vast way so to make such contribution almost indiscernible, and this has been demonstrated also by the fundamental work of Floyd E. Toole [15]: a panel of listeners was asked to evaluate many sets of home loudspeaker systems, ranging from very cheap to high quality ones, and, based on their relative scores, a classification followed, meaning that all the systems that got similar scores were hard to distinguish to the ears. The same systems were measured in an anechoic chamber and grouped according to the obtained score, so that also their grouped frequency responses could be considered indistinguishable from the point of view of human judgement.
The results of Toole clearly show that the highest quality systems will have a ± 5 dB tolerance for

frequencies above about 3 kHz, while "good" systems will have a dispersion of about +5 / -9 dB in the same area, with both classes presenting a ± 2.5 dB spread in the midrange area (see Figure 1).

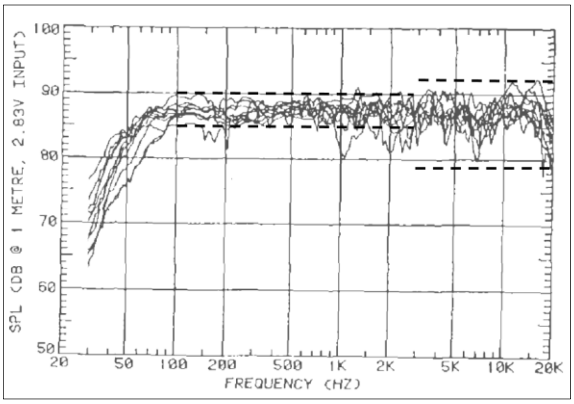

Figure 1. Frequency responses of "good" systems with envelope limits (dashed lines) [15].

It must be considered that the listeners of the Toole experiments worked in a very well controlled environment and experienced none of the above mentioned problems afflicting the listening experience inside a car, so that even the relatively large values that Toole derived for tolerance values are quite conservative if and when utilized in the automotive sector. Of course, it is not possible to affirm that examined grouped systems sounded exactly the same, but were close enough to be considered of the same quality and sound grade, so that the numbers produced by such well known experiment can give a guideline for EoL specifications.

4 Frequency Response (How to Fix Tolerances for EoL?)

Having indicated the possible tolerance limits using the studies done so far in the hi-fi sector, it is quite interesting to explore recent experiences in the automotive sector. Bellini [16] has studied the dispersion of a 90 samples batch of medium quality midrange loudspeakers, produced using components whose characteristics have been varied using the tolerance approved internally and by the customer; brought to the production line, this batch has been validated by the approved EoL test, so that it may be considered a reference set for this particular loudspeaker.

In Figure 2 we show the max/min envelope of samples referred to the average frequency response of the batch itself, so that dB values represent the ideal deviations from the ideal situation. We see that up to about 4 kHz the deviation is about ± 3 dB and then expands progressively to +8/-10 dB till the utilization limit of 12 kHz, comparing quite well with the results of the preceding paragraph for the "good systems".

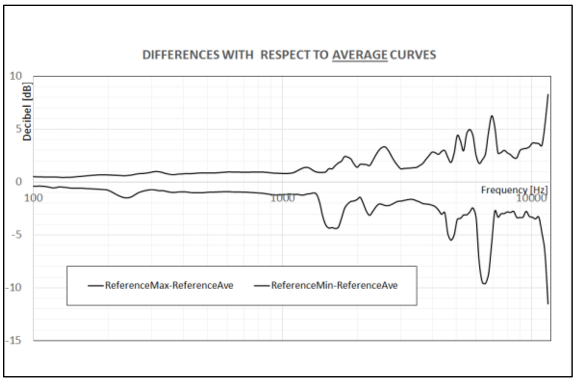

Figure 2. Envelopes of reference samples differences from batch average [16].

The original requirement for EoL of the Customer utilizing this midrange was identical to the design requirement, i.e. ± 2 dB in the range 120 Hz ÷12 kHz and this requirement has been tested on first mass production batches for a total of about 12'000 samples.

In Figure 3 the curves of Figure 2 are reported along with the ± 2 dB limits (dashed lines) and the max/min deviations of the 12'000 samples (dotted lines). It is immediate to note that many samples are out of the specs and we effectively get a scrap percentage of about 98%. In Figure 4 the approximate limits derived from the analysis of Bellini have been used and the scrap rate drops to about 10%: although a great improvement with respect to the original situation, this is still not acceptable from an industrial point of view: in Figure 5 we raised the upper limit by 0.7 dB and got a scrap rate of about 0.6%.

Following the proposal based on percentiles described in [12], we traced the curves of the 99th and 1st percentile and compared them with the limits used

in Figure 5, see Figure 6: using these percentile curves as limits the scrap rate is about 45%, and such a bad result can be explained by the fact that the percentiles are calculated for each frequency bin, and it can happen that a sample is fine for all frequencies but one and this would determine a scrap anyhow.
Finally, a different approach is presented in Figure 7, where the data have been smoothed to 1/3 octave (fine line with squares) and limits reduced to ± 3 dB in the midrange area expanding to ± 5 dB: scrap rate is about 0.7% but with stricter thresholds. This approach is based on the well-known fact that the human hearing system basically works as a 1/3 octave analyser, so it seems quite reasonable to use this averaging for loudspeaker evaluation.

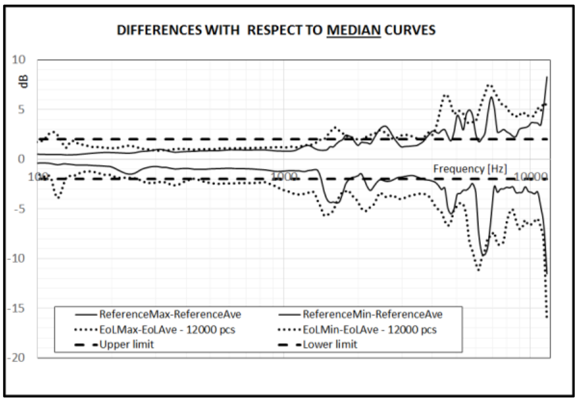

Figure 3. As Figure 2 but with added ± 2 dB limits and results from production batches samples (scrap rate 98 %).

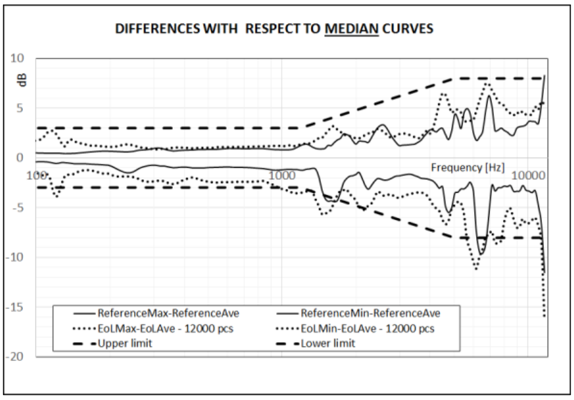

Figure 4. As Figure 3 but with modified limits (scrap rate 10 %).

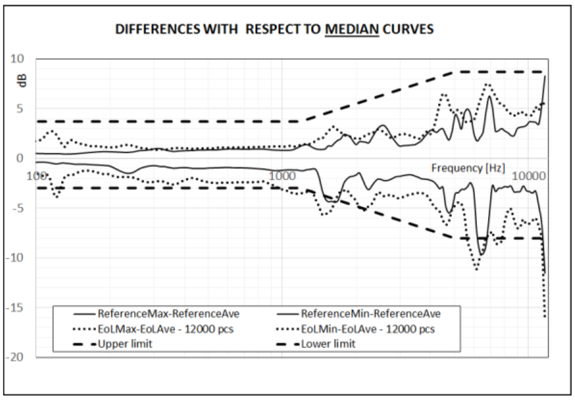

Figure 5. As Figure 4 but with raised upper limit (scrap rate 0.6 %).

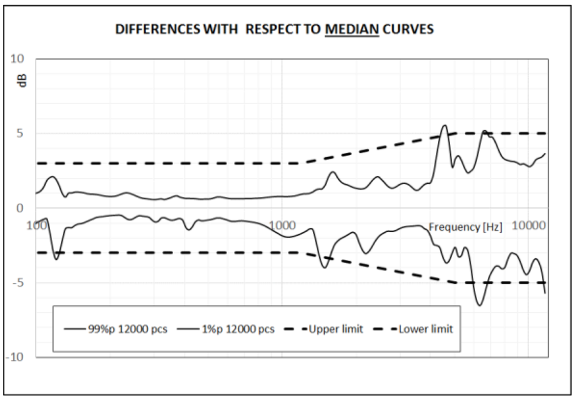

Figure 6. Percentile analysis of samples data (scrap rate 45 %).

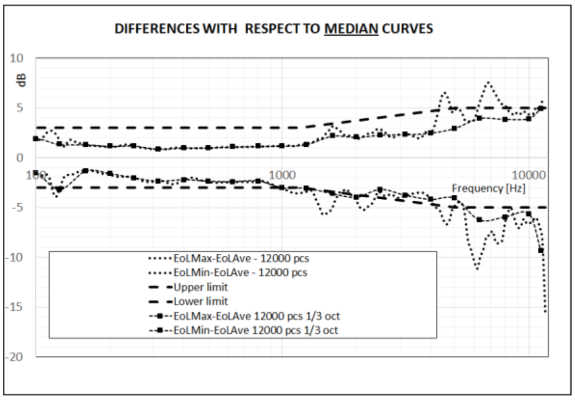

Figure 7. As Figure 5 but with data averaged at 1/3 octave and with adjusted limits (scrap rate 0.7 %).

5 Total Quality Factor (Bad Parameters or Wrong Limits?)

Total quality factor (Q_{TS}) is one of the parameters introduced by Thiele's [4] and Small's work [5], and since then widely used for identifying the damping properties of a loudspeaker driver around its first resonance frequency (f_S). One thing that is important to consider, however, is that Q_{TS} cannot be treated as an independent driver parameter.

The "fundamental" driver parameters chosen by Small were R_E, Bl, S_D, C_{MS}, M_{MS}, and R_{MS}:

- R_E DC resistance of driver voice coil,
- Bl force factor,
- S_D effective projected surface area of driver diaphragm,
- C_{MS} mechanical compliance of driver suspension,
- M_{MS} moving mass of driver including air load,
- R_{MS} mechanical resistance of driver losses.

That is a mathematically independent parameter set, i.e. each one may vary without necessarily causing a variation of the other ones (to be precise that is not completely true, as a variation of l can affect both R_E and Bl, but this can be neglected without too much confusion if we assume that Bl varies mainly due to the variation of B). Since the six above *fundamental parameters* (especially Bl and R_{MS}) are not easily measured, Thiele used instead another set of so-called "basic" parameters, in order to practically describe a driver and predict its in-box normalized frequency response at low-frequency.

The *basic parameters* used by Thiele were f_S, V_{AS}, Q_{MS}, and Q_{ES}:

- f_S resonance frequency of driver,
- V_{AS} volume of air having same acoustic compliance as driver suspension,
- Q_{MS} mechanical quality factor at f_S,
- Q_{ES} electrical quality factor at f_S.

By extension, also Q_{TS} is part of this set, being formed by both Q_{MS} and Q_{ES} according to the formula:

$$Q_{TS} = \frac{1}{\frac{1}{Q_{MS}} + \frac{1}{Q_{ES}}} \qquad (1)$$

If one is starting from a specific driver and he wants to design an enclosure around it, the approach of the *basic parameters* (f_S, V_{AS}, Q_{MS}, Q_{ES}, Q_{TS}) can be useful because they are relatively easy to be measured. But the *basic parameters* can be unpractical and sometimes cause of confusion when they are used to specify or design a driver from scratch, because they are not mathematically independent. For example a variation on V_{AS} due to a softer spider will also affect both f_S and Q_{TS}. That is not only a complication for the driver designer, but also for the driver Quality Control (QC) later on in the product lifecycle, as variations, especially for Q_{TS}, can be quite large in the real world (and we are here limiting the discussion just to the small-signal domain!).

So, whether simulating from scratch a new driver or trying to understanding why a driver is not sounding as expected, a better choice is to look at the *fundamental parameters* (R_E, Bl, S_D, C_{MS}, M_{MS}, R_{MS}) because they allow an effective diagnostic approach. The price to be paid is that the measuring effort is much more time-consuming in order to achieve an acceptable accuracy.

Let's look at the formula of Q_{TS} expressed only in terms of *fundamental parameters:*

$$Q_{TS} = \frac{\sqrt{\frac{M_{MS}}{C_{MS}}}}{R_{MS} + \frac{(Bl)^2}{R_E}} \qquad (2)$$

Expression (2) is useful to understand how the value of Q_{TS} can vary and how many driver components can be involved (or blamed, from a QC point of view). Here is a list of the possible causes of variation:

M_{MS} is mainly affected by:

- the masses of all the components that are moving along with the voice coil, glues included
- basket geometry (coupling additional air to the diaphragm)

C_{MS} is mainly affected by:

- spider stiffness
- surround stiffness
- temperature and humidity
- load history

R_{MS} is mainly affected by:

- the inner damping of the suspensions materials,
- the damping due to lossy air movement,
- currents induced by the voice coil
- temperature

- load history

Bl is mainly affected by:

- the magnetic properties of the magnet material
- magnetic circuit geometry assembly variations
- voice coil position

R_E is mainly affected by:

- wire diameter, length and material
- temperature

From the list above it is clear that the possible causes of variation for Q_{TS} involve so many components that it is practically very hard to keep its value within tight tolerances. In particular, it is generally accepted that a variation of Q_{TS} due to a shift of f_S should not be regarded as important [3]. Thus variations of M_{MS} and C_{MS} could be even counterproductive in the evaluation of the damping characteristics through Q_{TS} (to put that in perspective, consider that C_{MS} will vary enormously just due to the huge temperature range of the actual listening conditions inside a car! [14]). Q_{TS} is heavily affected by R_E and *Bl* which are also kept under control through Average SPL measurement. What is left out, last but not least, is R_{MS}, affecting directly the damping behavior but it is only weakly kept under control by other measurements (Frequency Response). Therefore measuring R_{MS} only instead of Q_{TS} could be an interesting EoL solution that should be deepened in the future.

A numerical example will make more evident how easily Q_{TS} statistical distribution can get wide. We have assumed that each of the five *fundamental parameters* affecting Q_{TS} can vary by ±10% around a nominal value. That tolerance is overestimated in some real cases, but in some other ones could also result too cautious [3]. The point here is not about the choice, but how the *fundamental parameters* variations (easily referable to the variations of the single components) build up for Q_{TS}. The nominal values are those of the driver of the case study considered in this paper, a typical 6”mid-woofer of a basic automotive audio system.

	R_E (Ω)	*Bl* (T·m)	C_{MS} (mm/N)	M_{MS} (g)	R_{MS} (N·s/m)
nom.	3.3	3.5	0.35	9	1.35
min.	2.97	3.15	0.315	8.1	1.22
max.	3.63	3.85	0.385	9.9	1.49

Table 1. Driver parameters nominal values and their considered ranges (±10%).

	Q_{ES}	Q_{MS}	Q_{TS}	Q_{TS} variation
nom.	1.37	3.76	1.00	-
min.	0.92	3.09	0.71	-29 %
max.	2.05	4.61	1.42	+42 %

Table 2. Q_{TS} range corresponding to ±10% variation of the single parameters.

As described in Table 1, Q_{TS} ranges from -29% to +40% when the fundamental parameters range is ±10%. It is interesting to note that Q_{TS} range is asymmetric even if all the inputs variations are symmetric, and that is due expression (2) being nonlinear with the input parameters.

To simulate a statistical distribution we have used Gaussian variation of each parameter with standard deviation always equal to 2.5% of nominal value, so that the C_{pk} (Process Capability Index) of each parameter is 1.33, for the chosen tolerance of ±10%. The resulting Probability Density Function (PDF) is shown in Figure 8.

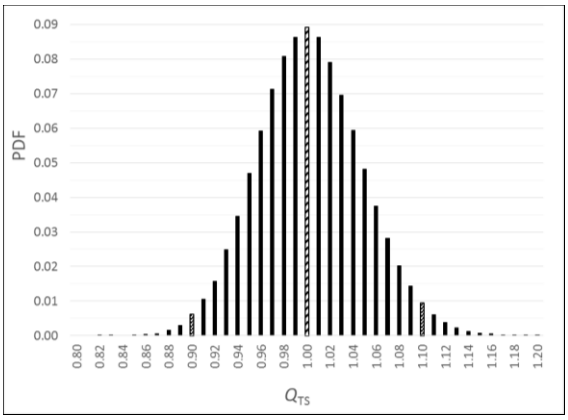

Figure 8. Probability density function (PDF) of Q_{TS} for the driver of Table 1.

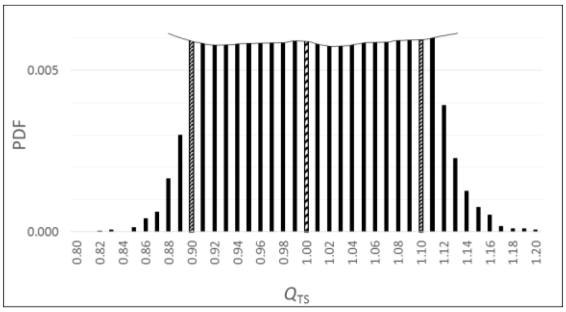

Figure 9. Same as Figure 8 but smaller PDF range visible. The asymmetric distribution is more noticeable as the values are further away from the center.

The simulation described above simply had the purpose of showing how expression (2) works and how the relative tolerance chain amplifies single components variations. However, we have until now not considered that real world distributions are rarely centered in the nominal values, and in many cases they are far from being symmetric. For example, the air gap magnetic induction *B* can realistically decrease much more than it can increase. For the purpose of this investigation, we chose to roughly account for it by shifting *Bl* Gaussian distribution down by just 2%, just to see what effect it has on the output (Q_{TS} variation). Being a squared factor, *Bl* plays the most important role in expression (2), and the effect is evident: Q_{TS} mean value increases by 3% when *Bl* mean value is decreased by 2% (all other parameters being unchanged).

Concluding this purely theoretical exercise on Q_{TS} variation causes, it's interesting to calculate what tolerances would be proper for the distribution of Figure 10. Following the numbers coming out of the last example, we need to put the lower limit at 0.83 (-17%) and the upper limit at 1.22 (+22%), in order to get $C_{pk} > 1.33$. The tolerance total width is thus 39% of the nominal value.

It is interesting to note that applying the same tolerances considered for the single *fundamental parameters* (±10%) we get $C_{pk} \simeq 0.7$.

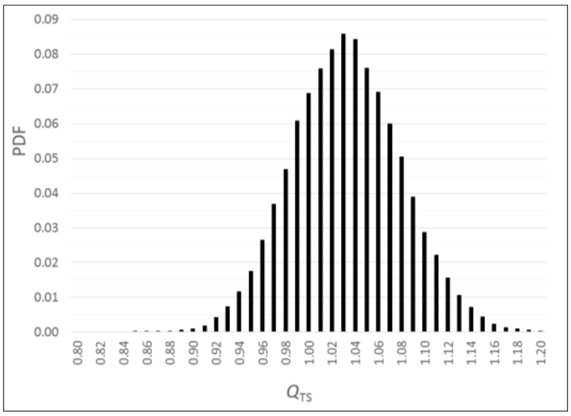

Figure 10. Probability density function (PDF) of Q_{TS} for the driver of Table 1. Parameters distributions are the same of Figure 8 except for *Bl* whose mean was shifted by -2%

Let's now take a look at real measurements.

In Figure 11 it is shown the distribution from the EoL measurements of over 30'000 parts (6" mid-woofer) with parameters not so much different from the virtual driver of Table 1.

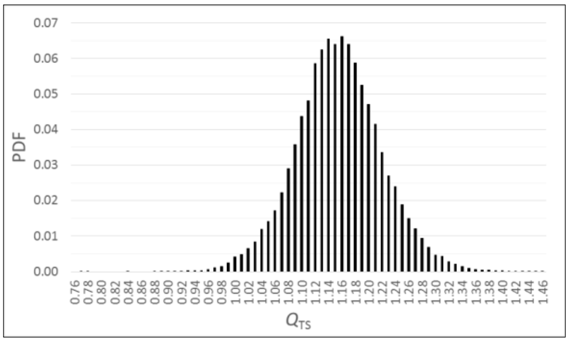

Figure 11. Probability density function (PDF) of Q_{TS} out of over 30'000 production drivers.

Considering over 30'000 samples produced in different batches, Q_{TS} standard deviation was around 5.5% of the mean value (in our theoretical example we had "only" 4.5%).

That is just one example of a real driver, but different designs will have different variations, depending on motor size, magnet type and material, etc.. Typically Q_{TS} standard deviations range between 5 and 7% of

the mean value, while offset of the mean value from the nominal value is up to 4÷5%.
Therefore, in order to achieve C_{pk} = 1.33, Q_{TS} tolerance specification, including distribution asymmetries, should be -24%/+32% for the typical automotive mid-woofer of Figure 11, but it could be necessary to enlarge it up to -30%/+40% for other driver designs such as a 4” midrange with a Nd-Fe-B magnet, for example.

6 Conclusions

This work has dealt with the problem of conflicting mass production tolerances definition between car and loudspeaker manufacturers, where the former tend to require very strict tolerances to guarantee ideally identical samples from any production lot. It has been demonstrated that such requirements are almost impossible to maintain because of the very nature of materials constituting a loudspeaker, and also that, from a perception point of view, there is no reason to fix such strict limits because of the insurmountable thresholds of the human hearing system. The best compromise solution seems to be, for frequency response, the use of data averaged at 1/3 octave, in a way similar to the actual human perception, with limits close to those determined by a long series of experiments with selected listeners. Another aspect of the problem is the selection of the measurements to be performed in an industrial EoL. Following also the conclusions of many other studies, it has been shown that an example parameter (Q_{TS}) that is usually regarded as an important one for the design of loudspeakers, is not well suited for EoL selection unless it is evaluated with generous (and asymmetric) limits. When specifying strict Q_{TS} tolerances, the risk is to cause scrap rates (and false failures! - Don't Throw the Loudspeaker Out with the Bathwater!), thus costs, incompatible with the automotive market standards.

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