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Woofer performance variance due to components and assembly process

Maria Costanza Bellini[1], Angelo Farina[1]

mariacostanza.bellini@gmail.com, farina@unipr.it

University of Parma, Industrial Engineering Dept., Parma, ITALY

ABSTRACT

This paper presents an experimental study of the main causes of scrap during the production of a woofer loudspeaker. After analyzing the most critical components of a transducer, samples with reference and modified components have been built and characterized in terms of frequency-response and linear distortion curves, and electrical, mechanical, acoustical parameters. In addition, a second set of samples has been built using reference components but varying the assembly process parameters; these samples also have been characterized as the previous ones. Measurements have been performed both in an anechoic chamber, along a production line and inside a car. By the analysis of acquired data, the authors have individuated the most influential components and assembly parameters in terms of required performance.

1. Introduction

This study is part of the future work mentioned in two past scientific papers [1,2]: the first presented at the convention of AES "*Berlin 2017- 142nd international Convention*", while the second at the AES 2017 "*International conference on automotive audio*" in San Francisco.
The investigation was done during a PhD program and it has been supported by a loudspeakers manufacturing company among the leader of the market so the research project has been developed at their research and production sites. The company is responsible for the design and production of audio and communication technologies for the automotive industry.
Scraps and rework costs are a manufacturing reality impacting organizations across all industries and product lines, but depending on the product there can be different variables that produce scraps. A loudspeaker is a very critical object, because it is made up of many components and the assembly process is composed by various steps; a little changing in one of these can produce a big amount of scraps during the production. In addition, in a loudspeaker most of the dominant nonlinearities, which generate scraps during the EoL (End of Line) final control, are caused by the transducer principle and they are directly related with the geometry and material properties of the motor, suspension, cone and enclosure. For these reasons, the goals of this study are to improve the quality of the transducer since the development phase reducing the variance and the number of pieces which will fail the EoL test, and to examine the actual influence of measured differences in a loudspeaker working environment.

2. Case study: components and assembly process

The study investigates the behaviour of one typical speakers used in the automotive sector: a woofer with a diameter of 165 mm designed to operate between 80 Hz and 9 kHz.
The research can be divided in two parts: the first concerns the influence on sound quality of the individual component of the loudspeaker, while the

second analyses the influence of the assembly process; so, samples with physical characteristics that slightly differ from those used in production have been realized on purpose. For comparison, also two sets of ideally "perfect" reference speakers have been built.
All loudspeakers are characterized in terms of frequency-response curve, total harmonic distortion (THD) and electrical, mechanical, acoustical parameters.

2.1 Loudspeaker components

As said before, a loudspeaker is a complicated device, because there are several components in it and each of them influences the behaviour and quality of the unit. Also, the interaction of various components creates different results in the performance.
Based on the ample experience of the company supporting this research, only the most critical variables, in terms of possible cause of scrap, are selected [3]. The maximum and minimum tolerances used in this work are real, due to the fact that the scope of this research is to obtain reliable results that can be useful for the company to improve its production.
For corporate privacy the tolerances used cannot be declared, but it is important to know that they are true tolerances required and accepted by the customer.
The physical components changed in this part of the study are:

- weight of cone
- thickness of membrane's edge
- pulp quality of the membrane
- electrical resistance of voice coil
- stiffness of spider
- weight and thickness of dust cap

For each variable of the list above three pieces are built at the maximum tolerance and three at the minimum tolerance. Regarding the pulp quality, the percentage of presence of material in the cone is changed (two in this case). Obviously, also three reference samples (with nominal values used during the production line) are built and samples with mixed flaws are not produced; so only one parameter is changed at time. In total, 39 loudspeakers are built.

2.2 Loudspeaker assembling process

During this second part of the study the assembling process of loudspeaker is simulated and the influence in the performance of the device is analysed. To do this, some special "offline equipment" (the same used during the production line) is used and the glue between components is altered.
There are various ways to assembly together the single components of loudspeakers depending from materials, glue and from the model. For example, in this specific case, the spider, the membrane and the voice coil are assembled together in two different steps, on the contrary for the midrange analysed in the other mentioned papers [1, 2].
The used tolerances are values that the company generally employ to produce loudspeakers, so this permits to obtain reliable results. Also in this case devices with the maximum and minimum production tolerances are produced and the involved variables are selected according to the experience of the company.
In detail, are changed:

- Gluing of moving part of speaker
- Gluing between dome and cone
- Black paint for damping on the cone
- Position of voice coil (Coil IN and Coil OUT)

For each entry of the variables descripted above, ten speakers were built: five with maximum tolerances, five with minimum tolerance and five reference ones. Also in this case, like the experiment on loudspeaker's components, samples with mixed flaws are not produced: in total 45 defected loudspeakers are built on purpose.

3. Measurements sets-up

Thanks to the support of the company mentioned in the introduction, three different tests are performed to analyse the loudspeaker's performance.

All assembled loudspeakers, modified and nominal, were tested in a certificated anechoic chamber, during a real production line and inside the vehicle.
All devices are characterized in terms of frequency response and linear distortion curves, and electrical, mechanical, acoustical parameters.
For the first two measurements, it is used an equipment developed by a German company (Klippel): currently, the system is the standard of measurement for the automotive industry. Instead, inside the car SpectraRTA software is used, driving an external sound card “Roland – UA – 25EX” and to two microphones “Behringer ECM-8000

3.1 Anechoic chamber measurements

In the laboratory two different measurements with two different Klippel Analyzer [5] are performed. One is dedicated to acoustical measurements in the anechoic chamber and it is used to evaluate the transfer function between two signals at the desired resolution and bandwidth: through this test the frequency response curve and the graphic of the total harmonic distortion (THD) are obtained. The measure is done with a standard baffle and the microphone is put at one meter of distance from loudspeaker according the normative IEC EN 60268–5 [4]. The other measurement in the laboratory is dedicated to identifying the lumped parameters of the transducer’s equivalent circuit and the linear, nonlinear and thermal parameters.

3.2 EoL measurements

To test loudspeakers during the production line a different Klippel system has been employed, namely a Quality Control - QC one. The tool provides a simplified user interface with the necessary results required for manufacturing. The tests to do can be split into several subtests, each with an individual stimulus. This allows shortest test cycles using most critical signals for testing at the physical limits [7].

3.3 Measurements inside the car

Inside the car only one test is performed that permits to characterize loudspeakers in terms of frequency response. The harmonic distortion is not measured because of the complexity of acquiring reliable curves in the vehicle due to several reflections created by different materials and surfaces. Moreover, for this measurement a different system, namely SpectraRTA, is used
The software is a PC-Based FFT Spectral Analysis program. Spectra works in conjunction with the sound card of the computer or any other external A/D - D/A converter system. After plugging the signal to be analysed into the Line-In or Mic Input of the sound card or converter system, the software uses the sound system to perform an "Analog-to-Digital" conversion of the audio signal.
This digitized audio signal is then passed through a math algorithm known as a Fast Fourier Transform (FFT) which converts the signal from the time domain to the frequency domain.
The tools used in the study for the measurement are:

- A CD reproducing a pink noise
- External amplifier
- SpectraRTA installed in a PC
- Sound Card linked to PC through USB
- Two microphones (the actual recorded signal is the average of those)

The microphones are positioned on the rear right seat and the horizontal distance between them is 17cm. Fig. 1 shows the set-up of the measurement and Fig 2 shows the position of the microphones inside the car.

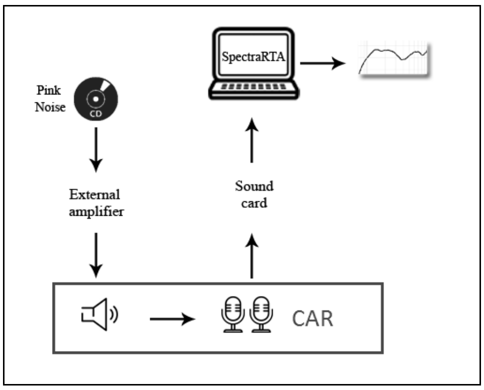

Figure 1: Set-Up for the measurements inside the car

Figure 2: The microphones are positioned on the rear right seat inside the car

The tested woofer is positioned on the right rear door of the production car used for the measurements and Fig. 3 shows the system configuration.

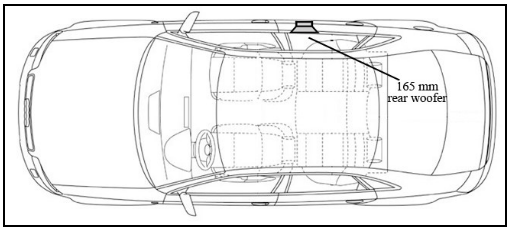

Figure 3: Position of woofer in the car production used for the measurements

4. Measurements and data analysis

The results of the measurements cannot be shown in their entirety for corporate privacy remembering that the research has been supported by loudspeakers manufacturing company, but interesting conclusions will be derived anyhow.
Each curve presented is the average of the three or five measured curves of the single defect of components or assembly process; each graph represents an ideal situation, because all components are in tolerance and in each loudspeaker only one parameters at the time is modified and always respecting the maximum and minimum tolerance used internally to the company and accepted by the customers.

Some graphs with the curves of differences between reference samples and modified samples are calculated, but not presented in this session due to the available space.

4.1 Modified components parameters sample

As a general observation, we may say that the results obtained both from laboratory and EOL lead to the same conclusions and show the same critical components, instead the measurements inside the car reveal some different conclusions.
Below they are presented the graphs of frequency response (Fig.4, Fig. 5, Fig. 6) obtained by three measurements and the harmonic distortion from the lab and EOL test (Fig.7, Fig. 8).
From the images of frequency response, it can be noted that there is a dispersion of 6 dB both during laboratory and EoL measurements. These differences start more or less at 3200 Hz and at the same frequency in the THD there is an evident peak. The peak could derive from the membrane of the Woofer, because at that frequency band the cone predominates the performance of the speaker. Instead, inside the car these differences are reduced, but however the same critical components arise.

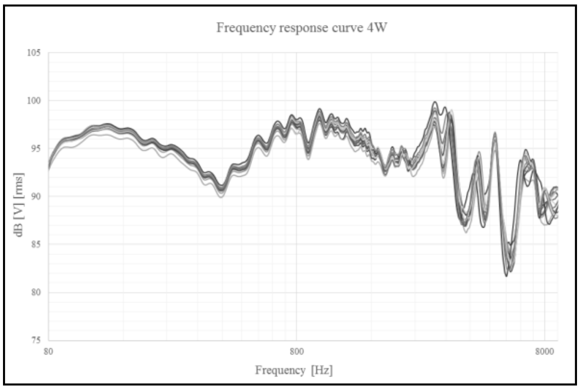

Figure 4: Frequency response curve of lab measurements

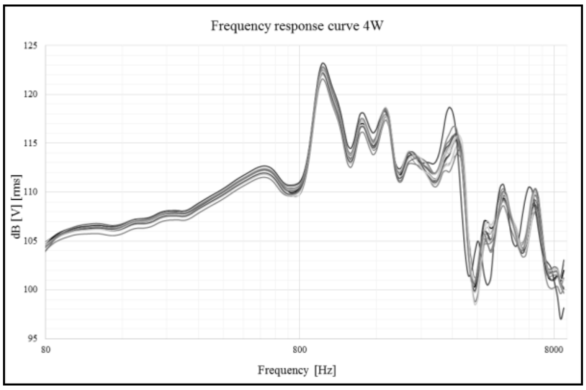

Figure 5: Frequency response curve of EoL test

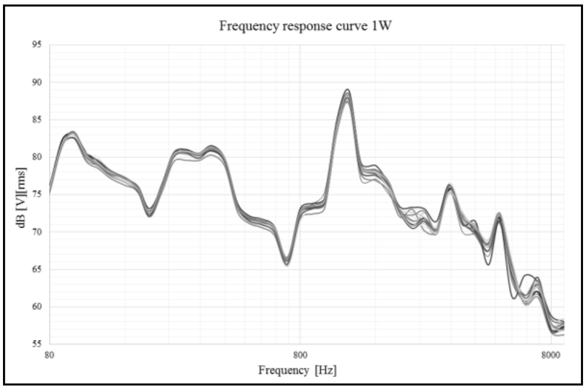

Figure 6: Frequency response curve of car measurements

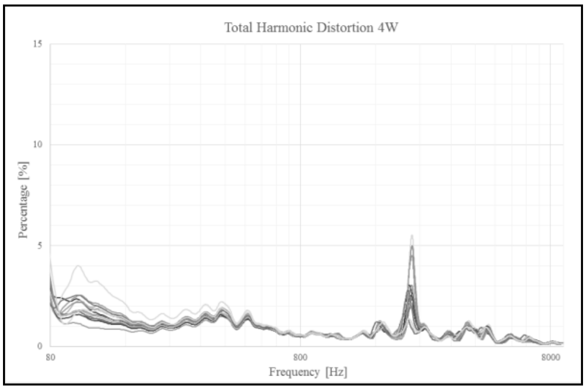

Figure 7: THD curves of woofer with variation on assembly process obtained from anechoic chamber measurements.

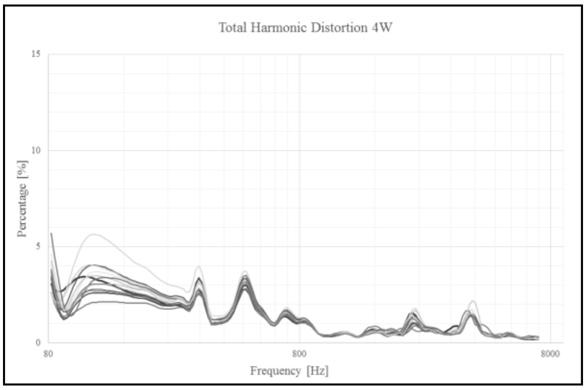

Figure 8: THD curves of woofer with variation on assembly process obtained from EoL test.

On the contrary, the analysis of electrical, mechanical and acoustical parameters underlines no evident variations in their values and their behaviour is quite predictable; for these reasons, no results have been reported in the paper.

For a better analysis and to derive more reliable conclusions about the most critical components, a 1/6 octave averaging smoothing has been used for frequency responses. Then the differences between reference samples and modified components ones have been calculated and plotted and then added on the entire frequency band of 40-9000 Hz. Doing so, it has been possible to concentrate all deviations in a single number for each type of modified component.

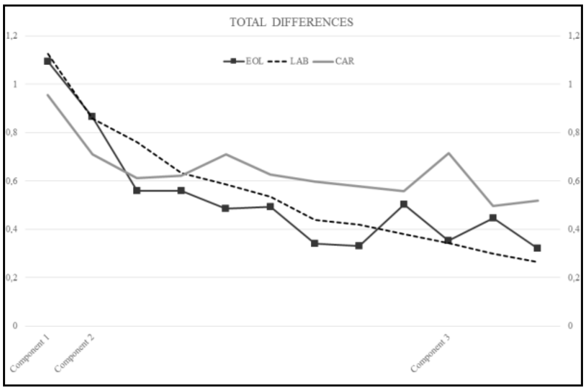

Figure 9: Graphs with the maximum summation value reached by each modified component during lab, EOL and car test (all results not shown for confidentiality reasons).

Figure 9 shows the graph of such results for the three measurements (lab, EoL and car) and Table 1 is a numerical representation of this.

From the image above, it can be noted that the relevance of the modified component is not perfectly coincident among laboratory, EoL and car: if we examine Figure 9, it is evident that Component 1 is the most important one for all situations, but, while Component 2 is the second one for lab and EoL, it is not so for the car measurements, where Component 3 predominates.

However, a simple correlation analysis shows that between the three measurements regarding the modification of components, there is a minimum Pearson coefficient of 0.78. From the theory it is known for $\rho>0.7$ there is a strong correlation between two matrixes.

Table 1: Averaged on the entire frequency band of 40-9000Hz of differences between reference samples and modified components after the analysis of 1/6 octave. It's a numerical representation of Figure 9.

	CAR	EOL	LAB
Component 1	0,95	1,09	1,13
Component 2	0,71	0,87	0,86
	0,61	0,56	0,76
	0,62	0,56	0,63
	0,71	0,49	0,59
	0,63	0,49	0,53
	0,60	0,34	0,44
	0,58	0,33	0,42
	0,56	0,50	0,38
Component 3	0,72	0,35	0,34
	0,50	0,45	0,30
	0,52	0,32	0,27
Pearson (Car/EoL)	0.78		
Pearson (EoL/Lab)		0.92	
Pearson (Car/Lab)	0.81		

4.2 Assembly process sample

As before, also in this case from the analysis of electrical, mechanical and acoustical parameters there appears to be no significant piece of information for the goal of this work, so no results have been reported.

In addition, the effects of the assembly process deviations seem to be less important than that due to the variations of the properties of the components; in fact, from the analysis of measurements any process deviation doesn't influence in a significant way the performance of the samples. The minimal differences between samples with deviating assembly parameters and the nominal ones happen only at very high frequencies and they are not so relevant (less than 2.7dB). For these reasons, it is only presented one graph of measurements done as demonstration also of the others.

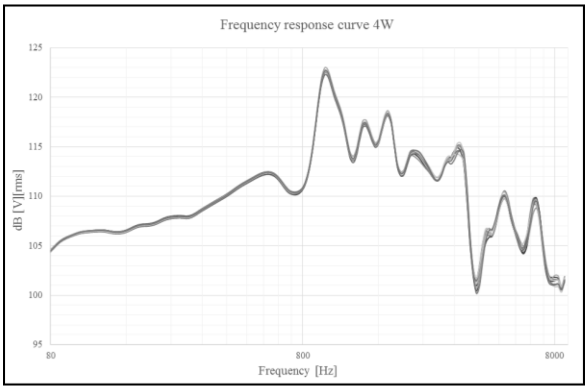

Figure 10: Frequency response curve of samples with variations of assembly process obtained after the EoL test

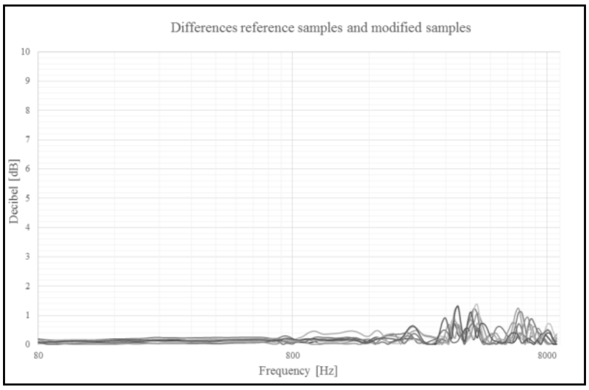

Figure 11: Differences calculated between an average of reference samples and samples with variations of the assembly process (EoL).

Fig. 10 shows the graph of frequency response curve of the EoL test, and Fig.11 show the differences calculated between the average frequency response of reference samples and averages of modified samples from the same measurements.

5. WOW – "WORST OF THE WORST

Through the comparison of the measurements done in the anechoic chamber, the influence of each modified component or assembly process has been evaluated and the most relevant ones in terms of approved loudspeaker performance have been determined.

After the ending of the measurements of the first set of samples (samples with modified components), the components which influence more the response of the loudspeaker had been individuated thanks to the analysis at 1/6 octave (Fig. 9 and Table 1). The results obtained from this analysis are used to build the special samples named WoW, where the acronym stands for "Worst of the Worst"; in total were built 5 WoW samples with the five worse components.

5.1 Results of measurements

The WoW samples were tested with all three-system described in the preceding paragraphs.

Fig. 12, Fig. 13 and Fig. 14 show the graph of differences calculated between the reference samples, samples with modified components and WoW samples. For confidentiality reasons the legend of the graphs is hidden, and only that of the WoW is showed.

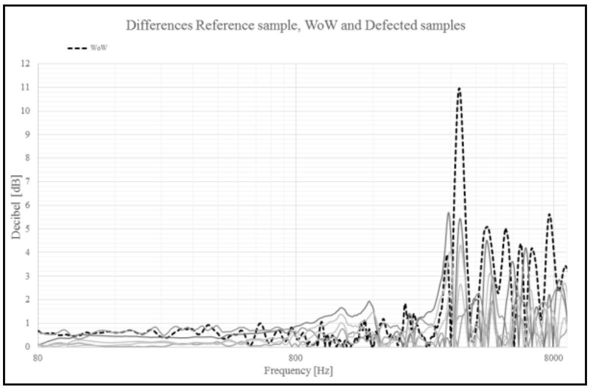

Figure 12: Graphs of differences calculated between an average of reference samples, WoW and modified components (Lab)

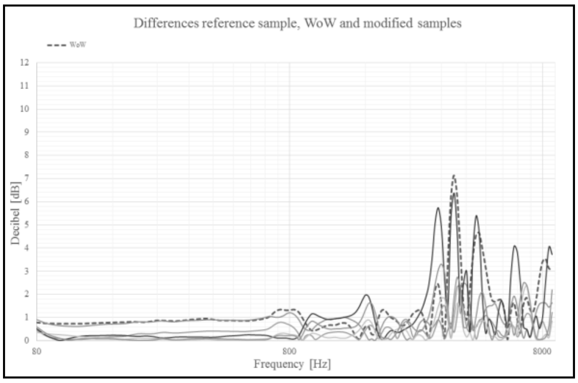

Figure 13: Graphs of differences calculated between an average of reference samples, WoW and defected components (EOL)

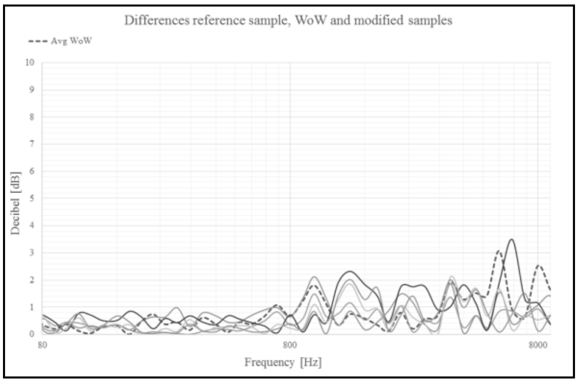

Figure 14: Graphs of differences calculated between an average of reference samples, WoW and defected components (Car)

From the graphs above it can be affirmed that the WoW samples are not the worst respect the loudspeaker with modified components: seems there be a sort of compensation in the WoW samples, producing a better averaged curve than the averaged curve of the single defects. Actually, the components don't interact with each other producing much higher deviations with respect to the single modified components (only exception is the difference peak in lab measurements at about 3.2 kHz). The graphs of difference between reference samples and WoW illustrate also how the big differences, especially at high frequencies, emerged from laboratory and EoL tests are not so evident inside the car. In all measurements the harmonic distortion curve is much lower than the other curves.

5.2 Data Analysis

For a deeper analysis, each modified component was characterized by a percentage indicating its influence on WoW and the table below shows the value obtained from laboratory, EoL and car analysis.

Table 2: Percentage of influence of most critical components on WoW samples after three measurements and with an analysis of 1/6 octave

		dB	Linear	% WoW
LAB	WoW	3.28	1.46	
	Component 1	1.13	1.14	78%
	Component 2	0.86	1.10	76%
	Component	0.30	1.04	71%
	Component	0.42	1.05	72%
	Component	0.76	1.09	75%
EOL	WoW	1.33	1.17	
	Component 1	1.09	1.13	97%
	Component 2	0.87	1.11	95%
	Component	0.45	1.05	90%
	Component	0.33	1.04	89%
	Component	0.56	1.07	92%
CAR	WoW 1	0.79	1.10	
	Component 1	0.95	1.12	102%
	Component 2	0.71	1.09	99%
	Component	0.50	1.06	97%
	Component	0.58	1.07	98%
	Component	0.61	1.07	98%

In the table the column of dB contains an average calculated from the differences between reference and flawed sample in the range 80 Hz – 9 kHz, while "Linear" column is a simple conversion of the dB value: the percentages in WoW column are obtained by the ratio between the linear value of each component and the linear value of the WoW. It is evident that the mixing of components does not increase the differences between reference and modified samples.

Conclusions

The study has showed some interesting results and it will be used by the company as a tool of improvement for the production and design of loudspeakers.

Obviously, the research can't stop here, because there are a lot of other fields to explore: this study is just a starting point for future investigations [8-9].

From the results it is evident that variations on components can produce more scraps rather than variations on assembly process; for this reason, it should be mandatory an accurate control of the physical and mechanical properties of components to reach a better design and quality.

The conclusions can be summarized in the list below:

- the results obtained from the three measurements (laboratory, EoL and car) lead to similar results, so underline the same critical components
- between the three measurements of the woofer there is a minimum Pearson coefficient of 0.78; so, it means strong correlation
- the results confirm the reliability of the quality controls utilized along the production line of the company
- the effects of the assembly process deviations seem to be less important than those due to the variations of the properties of the components
- the WoW samples follow more or less the behaviour of the single modified components according to the frequency band where each component is more influential
- the mixing of the worst components will not produce a higher distortion in the performance of loudspeaker

Although this work has considered one model of loudspeaker that is produced in very large numbers, the results and conclusions that we have obtained cannot of course be blindly applied to all kinds of transducers. For this reason, the procedure defined for samples preparation and data analysis formats will be replicated for future research. For example, future works will consider different type of transducers (i.e. tweeters) and materials (i.e. plastic cones).

A deeper investigation can be done, also, on the possible correlations between defected components

and their interaction in the frequency-response and distortion curves.
Because in this study, due to the time available and the organization, choices were made and a real experiment plan (DOE) was not implemented to create all the probable mixings between the various components.

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