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Effectiveness of Exotic Vapour-Deposited Coatings on Improving the Performance of Hard Dome Tweeters

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ABSTRACT

The audio industry is constantly striving for new and different methods with which to improve the sound quality and performance of components in the signal chain. In many cases however, insufficient evidence is provided for the benefit of so-called improvements. This paper presents the results of a scientific study to analyse the effectiveness of applying vapour-deposited Diamond-like Carbon, Chromium and Chromium Nitride coatings to aluminium and titanium hard dome tweeters. Careful attention was paid during the processing, assembly and measurement of the tweeters to ensure a control and equal influence of other factors such that a robust analysis could be made. The objective results were supplemented with listening tests between the objectively most significant change and the control.

1. INTRODUCTION

Small iterations in the development of the traditional electrodynamic loudspeaker units continue to be made. However, in most cases, these iterations relate to changes in component materials, or combinations of different materials, where the fundamental design of the transducer remains the same. In recent years, more exotic materials have found their way into loudspeakers with the aim of improving acoustical performance – in fact, there seems to be no limit to the exotic nature of materials included; for example Beryllium, Boron, Magnesium, ceramics and Diamond-like Carbon have found their way into tweeters and other loudspeaker units - either as solid membranes themselves or as coatings in order to improve sound performance.

In general, a supplier is actively seeking new products with which to satisfy the customer's (or sales and marketing department) need for product headlines and it was partly with this motivation, that the work presented in this paper was initiated. From an engineering point of view however, we did not simply want to implement a solution without understanding the performance benefits (or indeed, if there were any benefits at all). Particularly in the business-to-business marketplace, the customer or OEM often demands robust documentation for the benefits of new technologies - and a balance must be struck between performance and cost. Unfortunately, the audio industry is not always that good at providing robust scientific documentation for advertised benefits of technologies employed. Indeed, some of the earlier literature on the subject of exotic materials used in speaker membranes is sketchy at best.

2. PHYSICAL VAPOUR DEPOSITION

Physical Vapour/Vapor Deposition (PVD) is a technique dating back to the 19th century but has found new appreciation following the rapid advancement of technology and industrial methods since the 1960's and particularly in the last two decades. The technique is a method to deposit thin films by condensation at atomic level of a vapourized coating material onto a target surface. The process occurs at high temperature (typically several hundred degrees Celsius) and in an evacuated chamber filled with pure argon. The condensed atoms adhere extremely well to the target surface and the composition can be precisely controlled.

Application of PVD coatings is used increasingly in industry for corrosion resistance and to reduce the surface friction coefficient to very low levels of, for example, nuts and bolts, and in precision tools such as medical drill bits and other specialist cutting equipment.

In acoustical applications, the basic intention of applying a PVD coating is to increase the overall stiffness of a loudspeaker membrane by coating the underlying substrate with a harder layer or layers. Earlier studies [1] have shown PVD to be a suitable for practical applications. In theory, increasing the stiffness causes the break-up frequency of the membrane to be shifted upwards in frequency and thereby increases the bandwidth of the loudspeaker. A secondary desire can be to increase damping of resonances in the membrane.

Figure 1 The CemeCon industrial PVD machine.

Figure 1 shows the CemeCon industrial PVD machine used for making the coatings described in this paper. The PVD technique is a so-called 'line of sight' process such that complex target surface geometries must be rotated on several axes during the process to ensure even coating. This can be done by mounting the target parts onto a carrousel that can mechanically rotate during the coating process to ensure an even coating across the target surfaces. Figure 2 shows the doors open to the vacuum chamber of the above machine in which the samples were placed on a carrousel similar to one seen in the centre of the chamber.


Figure 2 The open PVD vacuum chamber.

For this experiment, the raw tweeter domes were mounted horizontally (facing upwards) and experienced a 3-fold planetary rotation during the coating process. Figures 3 and 4 illustrate the carrousel in more detail and mounting of the raw tweeter domes on it.

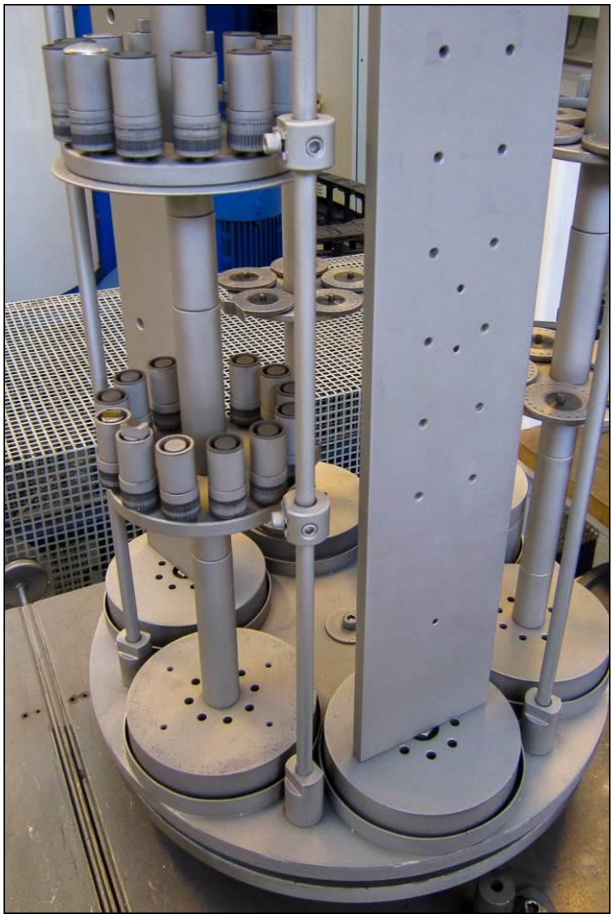

Figure 3 The carrousel for the PVD machine.

Figure 4 Mounting of raw domes on the carrousel.

In order to avoid contamination and to ensure ideal adhesion of the coatings, the raw domes were carefully cleaned before the coating process as follows:

- 2-3 minutes of ultrasonic cleaning in acetone
- Flushing in 2 baths of ethanol
- Drying with compressed nitrogen

Small steel dummy elements were also included in the coating process in order to allow the evenness and thickness of the coatings to be verified afterwards. This was done using the calotte cross-section grinding method in which a rotating steel sphere and abrasive liquid are used to mill a crater through the coating layers and into the substrate of the dummy elements. Optical microscopy is used to analyse the geometry of the rings found in the crater, as shown in figure 5, from which the precise layer thicknesses are calculated. Note that the layer thicknesses are of the order of micrometres (μm).

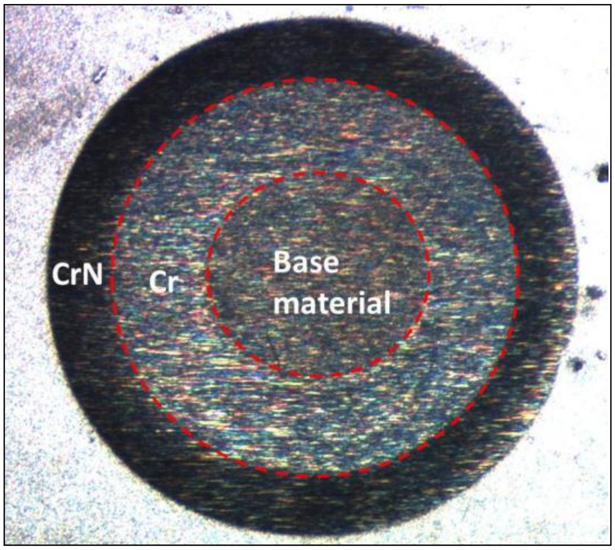

Figure 5 Example of a crater for calculating layer thicknesses (courtesy of Klaus Pagh Almtoft).

3. SUBSTRATE DOMES & COATINGS

With a coating method available, the next step was to decide which tweeter dome base (substrate) or bases to use and in combination with which coatings. For the project to be feasible both in time and cost, it was clearly advantageous that the domes could be assembled in a drive unit that was in production at a drive unit manufacturer. Therefore, the Scan-Speak 19 mm D19 (shown in figure 6) and 26 mm D26 tweeters were selected. Furthermore, it would be possible to have both aluminium and titanium substrates which are of course very common hard dome tweeter membrane materials and are therefore extremely relevant for this study.

The raw 19mm aluminium and titanium domes used in the experiment had thicknesses of 50 and 26 μm and masses of 51 and 45 milligrams respectively. The increased strength of titanium allows for a thinner membrane (almost half the thickness of aluminium but ending with similar masses due to the increased density). The raw 26mm aluminium and titanium domes used in the experiment had thicknesses of 46 and 24 μm and masses of 82 and 73 milligrams respectively. The raw domes where available so coatings could be applied as described earlier (obviously it is not possible to apply these coatings in an assembled loudspeaker drive unit).

In terms of coatings, Diamond-like Carbon or DLC, has come into fashion within the loudspeaker industry due to increasing feasibility of modern manufacturing processes and its hard and stiff material properties (and probably also because of the appealing sound of the word ‘diamond’). Therefore we wanted DLC to be included in the study. Furthermore, Chromium and Chromium Nitride can be applied using the PVD technique and these materials also exhibit great resistance to deformation, having elastic modulus’s significantly greater that the substrates in question and also equivalent to DLC and Titanium Nitride. Table 1 lists common physical properties for relevant materials.

Figure 6 Standard production version of D19 tweeter.

Material	Physical Properties			
	Density (g/cm^3)	Young’s Modulus (GPa)	Vickers Hardness (GPa)	Coefficient of thermal expansion ($10^{-6}K^{-1}$)
Beryllium (Be)	1.9	~ 290	~ 1.7	11
Boron (B)	2.4	400	~ 45	6.0
Aluminium (Al)	2.7	~ 70	0.16 - 0.35	23
Titanium (Ti)	4.5	~ 120	0.83 - 3.4	8.6
Titanium Nitride (TiN)	5.2	200 - 650 [2]	2.4	9.4
Chromium (Cr)	7.2	280	1.1	4.9
Chromium Nitride (CrN)	5.9	~ 200	~ 2	-
Diamond-like Carbon	~ 1.9	> 200 [3] 500 - 533 [4] 230 [5]	> 40 [3] 80 - 100 [4] 29 [5]	-
Diamond	~ 3.5	1050 [4] 910 [5]	56 - 102 [3, 4]	1

Table 1 Physical properties of relevant materials (in most cases rounded to 2 sf. for simple comparison).

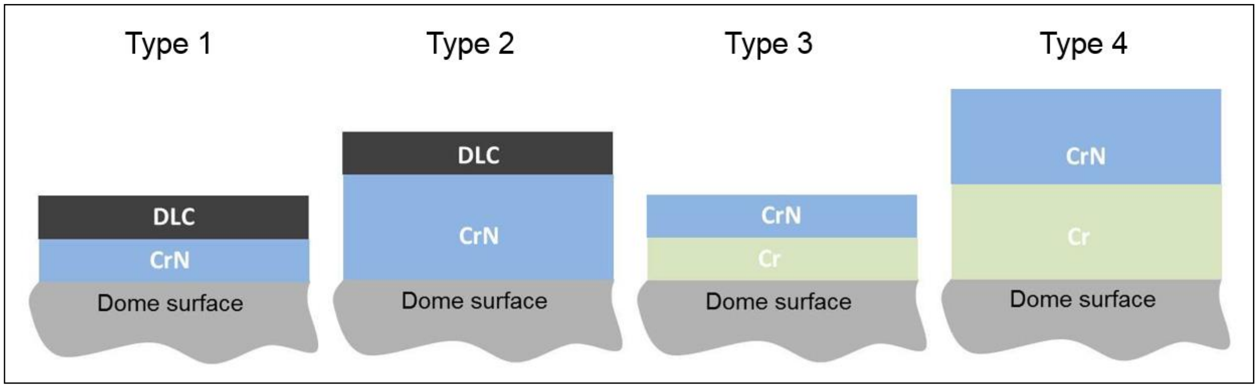

Figure 7 Illustration of the coatings chosen for the study (courtesy of Klaus Pagh Almtoft).

It is important to note that layer thicknesses possible with DLC are relatively limited. Also, experimental data [3, 4, 5] for the Young's Modulus and Vickers Hardness of DLC vary substantially due to the range of polytype configurations of the carbon atoms that occur in the material and the limited thickness of the layers produced on which to measure. In this respect, Chromium and Chromium Nitride can be 'grown' to greater layer thicknesses. Additionally, logical thought made us predict that thicker layers would have a larger effect on the performance and so the study should also look into different layer thicknesses as well as material types.

Combining these arguments with the feasibility and time needed for the PVD processes, four layer types where chosen for the study as illustrated in figure 7.

Table 2 indicates the anticipated layer thicknesses in μm based on the experience of the tribology team at the Danish Technical Institute and the timings used to deposit these types of layers previously.

Type	Cr	CrN	DLC	Total
1	-	1.5	1.5	3.0
2	-	8.0	2.0	10.0
3	1.5	1.5	-	3.0
4	4.0	4.0	-	8.0

Table 2 Anticipated layer thicknesses in μm.

The actual layer thicknesses achieved in this study including percentage change relative to the substrate and masses of the domes are documented in section 6.

4. EARLIER WORK

Earlier work [1] presents results of coating a titanium hard dome tweeter with a Boron layer using the PVD technique. However, the paper proposes to document positive results after measuring only two loudspeakers, one with and one without the coating.

Work by Sakamoto et al. [6] presents results of coating a 20 μm thick titanium tweeter dome with a 0.8 μm layer of plasma diamond film (DLC) on both sides. The results advertise an increase in break-up frequency from 24 to 37 kHz. Again it appears only single loudspeakers have been measured (one with and one without the coating) and the paper is largely theoretical in nature.

A good paper by Buck et al. [7] compares the performance differences in using solid beryllium diaphragms versus aluminium and titanium in large format compression drivers. Theoretically they predict an increase in break-up frequency of 2.5x however, the measurements illustrate an increase of the upper cut-off by approximately 40% only. Once again conclusions are drawn based on measurements of single loudspeaker units of each diaphragm material.

Another paper discussing the benefits of DLC coatings [8] applies a 0.12 μm layer of diamond-like carbon to a 25 μm thick substrate in a 10.5 mm diameter tweeter with four different deposition areas (none, dome only, surround only, dome and surround). Surprisingly, when quantifying the improvements of using DLC, the authors conclude that the layering (which was ~1/200th of the substrate thickness) gave the up to 1.2 dB differences in frequency response when measuring the different depositions across different loudspeaker parts!

These examples of earlier published work on the subject of using exotic membranes or coatings to improve the performance of loudspeakers should help to illustrate that the evidence is limited, particularly by the fact that only single loudspeakers have been compared. As most are generally aware, large variations can be observed between loudspeaker drive units despite them being of the same type and production batch – without different materials or components being employed. These differences are invariably large at and above the upper operating limit of the loudspeakers' range.

5. EXPERIMENTAL METHOD

In this study, we wanted to make a strong attempt at achieving statistically sound results and thus be in a position to draw robust conclusions.

Therefore a total of 200 raw domes were included in this study. These were divided into one-hundred 19 mm and one-hundred 26 mm domes. Each of these two groups included 50 aluminium and 50 titanium domes.

Each of these four groups of 50 domes were further divided into five sub-groups of 10 pieces each. The raw domes were divided into the sub-groups at random, such that any differences in the raw material should be spread evenly across each sub-group. The first sub-group was deemed a control group '0' that would not be coated and thus serve as a reference. The remaining four sub-groups had the coatings applied as illustrated in figure 7. Table 3 indicates the naming given to the sub-groups for the 19 and 26 mm sizes.

Type	Description	Al	Ti
0	Control (raw domes)	A0	T0
1	CrN + DLC thin	A1	T1
2	CrN + DLC thick	A2	T2
3	Cr + CrN thin	A3	T3
4	Cr + CrN thick	A4	T4

Table 3 Naming of the sub-groups.

Prior to coating, the raw domes in sub-groups 1 to 4 were cleaned as described in section 2 before being put through the PVD coating processes.

The coatings in each case where only applied to the visible outer/upper side of the membrane.

Following the coating processes, the domes were visually inspected, weighed and the thicknesses of the actual coatings was determined using the dummy elements as explained in section 2.

The domes were next delivered personally to Scan-Speak for assembly on their normal production line for these models of tweeter. The assembly of the functional tweeters was made repeatedly in the specific order A0, A1, A2, A3, A4, T0, T1, T2, T3, T4 until all were assembled. This method was to ensure that any variations in assembly of the complete loudspeaker units would influence each group equally. This is paramount as the assembly process, including mechanical, gluing and component tolerances and environmental changes will contribute to differences between the assembled loudspeakers.

The assembled loudspeakers were now delivered to Bang & Olufsen for assessment. Firstly, the small 3-legged plastic protective grid as can be seen in figure 6, was removed from all tweeters. Next, all tweeters were inspected visually and some parts where discarded from the study due to either the dome being visually damaged or the moving assembly not being perfectly centred in the faceplate. A set of objective acoustical measurements were now performed:

- Frequency response on-axis in 2π (infinite baffle) at 30 cm distance, 2 Vrms, 1/48th octave resolution, 500 Hz - 90 kHz (19 mm) and 500 Hz - 45 kHz (26 mm).
- Frequency response as above but at 30^{o} off-axis
- THD as above to half upper frequency limit.

Measurements where made consecutively during a single day for each tweeter size. Again, the specific order A0, A1, A2, A3, A4, T0, T1, T2, T3, T4 was followed repeatedly until all were measured, such that any external influences on the measurements would be spread evenly across all parts. Measurements were performed using the following equipment:

- B&K type 4939 ¼" free-field microphone at zero degrees incidence with protective grid removed
- B&K type 4231 calibrator with DP0775 adaptor
- G.R.A.S. Type 12AQ preamplifier
- LynxTWO 192 kHz 24 bit PCI soundcard
- Hafler P500 analogue power amplifier
- SoundCheck audio analyser software

With the results of the objective measurements available, the average response of each measurement in each sub-group was calculated together with 95 % (2σ) confidence intervals at each data point. Furthermore, the average sound pressure level (sensitivity) was calculated in the frequency range 4 - 12 kHz.

The measurement results were analysed and conclusions drawn. Based on these discussions of the results, the study was extended to include a listening test between an average loudspeaker unit from two of the 19 mm sub-groups and subsequently also further objective measurements for comparison of these units.

The listening test was performed in a well-damped test room with the two 19 mm tweeters mounted flush in a 42 x 42 cm baffle with a vertical spacing of 11 cm (centre to centre). The listening axis was midway between the tweeters straight in front and the listening distance was 2.5 m resulting in a vertical separation angle of 2.5 degrees so there were no localization cues. The tweeters formed the treble section in a two-way set-up with a 24 dB/octave Linkwitz-Riley active crossover filter at 3 kHz. In order to maintain musical timbre, the lower frequencies were reproduced with a Genelec 1030A studio monitor placed vertically below and adjacent to the tweeter baffle. The set-up was built up with foam blocks and can be seen in figure 8. The set-up was hidden from view by a thin acoustically transparent curtain. The tweeters where driven by a PAS Audio 2002 PCA analogue power amplifier from a M-Audio Profire 610 soundcard. The listening test was controlled and run via a MAX patch on a MacBook. The patch was a slightly modified version of the ABX GUI from The University of Surrey [9] such that the listener had to identify whether X was A or B and in this case A and B where randomly assigned to the two tweeters for each of the six presentations of each of the six musical excerpts in a random order. Therefore each listener was presented with 36 tasks. The only difference in the signal path between the two tweeters was a gain difference of 1.0 dB to align the sensitivity of the two tweeters. The sound pressure level of the stimuli during the tests was 68-73 dBC (slow) at the listener position.

The blind test was repeated twice with 9 listeners in each round. The second test round was with the tweeter baffle rotated 180 degrees. The listeners where all people involved in audio product development and ranged from technicians to acousticians and experienced Tonmeisters. The age range of the listeners was 30 to 60 years.

Figure 8 Listening test set-up.

The 10 to 14 second duration looping musical excerpts used were selected for their recorded quality and treble content including strings, saxophone, sibilance and percussion and were taken from the following commercially available CD material (44.1 kHz / 16 bit stereo summed to mono for the tests):

- Michael Brecker - Escher Sketch
- Benjamin Britten - Young Persons Guide To The Orchestra
- Steely Dan - Gaslighting Abbie
- Jennifer Warnes - Bird on a Wire
- Doky Brothers - How Can I Help You Say Goodbye
- Joe Sample - Souly Creole

Following the listening test described. Four expert listeners were selected to repeat the test and indicate their subjective preference for A or B in each task.

Following the completed listening tests it was further decided to extend the objective measurements upon the two tweeters used in the listening tests. These further measurements where performed in the same physical 2π test set-up as already described but using a Matlab script on a PC and RME Fireface UCX 192 kHz / 24 bit soundcard. The impulse response of each tweeter was measured in order to calculate a waterfall plot.

6. RESULTS

Figure 9 illustrates the domes coated with CrN and DLC (appearing black). Figure 10 shows the control (raw) domes to the right and domes coated with Cr and CrN to the left (appearing steel-grey in colour).

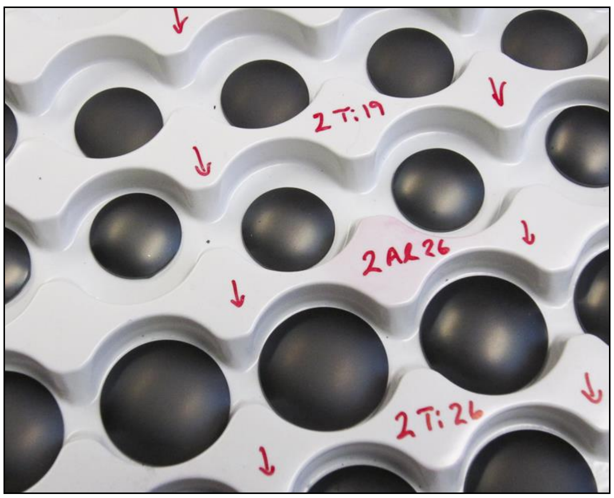

Figure 9 CrN/DLC coated domes.

Figure 10 Raw domes (right) and Cr/CrN coated domes.

6.1. Actual Layer Thicknesses

Table 4 indicates the actual layer thicknesses in µm of the four coatings and Table 5 indicates the percentage increase in thickness relative to the substrate.

Type	Cr	CrN	DLC	Total
1	-	3.2	2.4	5.6
2	-	9.4	2.2	11.6
3	1.3	1.4	-	2.7
4	4.7	5.2	-	9.9

Table 4 Actual layer thicknesses in µm.

Dome	Substrate µm	Coating µm	Increase %
19A1	50	5.6	11
19A2	50	11.6	23
19A3	50	2.7	5
19A4	50	9.9	20
19T1	26	5.6	22
19T2	26	11.6	45
19T3	26	2.7	10
19T4	26	9.9	38
26A1	46	5.6	12
26A2	46	11.6	25
26A3	46	2.7	6
26A4	46	9.9	22
26T1	24	5.6	23
26T2	24	11.6	48
26T3	24	2.7	11
26T4	24	9.9	41

Table 5 Percentage increase in dome thicknesses.

6.2. Actual Dome Masses

Table 6 indicates the average dome mass in each sub-group and the percentage increase in each case.

6.3. Objective Acoustical Measurements

Following the coating process, there were still at least 9 ‘healthy’ domes in each sub-group. Following assembly of the complete loudspeakers and visual selection prior to measurement, some parts where discarded due to damaged domes or non-centred assembly.

This resulted in at least 6 healthy parts remaining within each sub-group. Therefore, acoustical measurements where performed on 120 tweeters - sixty 19 mm and sixty 26 mm units – with 10 sub-groups of six units of each size. Figure 11 shows a healthy 19 mm tweeter with protective guard removed and mounted for test.

Dome	Mass milligrams	Increase %
19A0	51	0
19A1	56	10
19A2	60	18
19A3	56	10
19A4	63	24
19T0	45	0
19T1	51	13
19T2	58	29
19T3	51	13
19T4	66	47
26A0	82	0
26A1	94	15
26A2	109	33
26A3	92	12
26A4	110	34
26T0	73	0
26T1	84	15
26T2	105	44
26T3	81	11
26T4	115	58

Table 6 Average dome mass and percentage increase.

Figure 12 shows the on-axis frequency response measurement results for the aluminium control sub-group (19A0) and figure 13 shows the average response of the six loudspeakers in this sub-group with the confidence intervals. The uncertainty is particularly large in the range 30 to 36 kHz (at break-up) and above 70 kHz. Only in the tweeter's passband of 3 to 25 kHz are the results very certain.

Figure 14 shows the average an-axis response in each of the 19 mm aluminium sub-groups together with an inset of each sub-group at break-up (20 to 40 kHz) with all six individual responses (grey) and the average (black).

Figure 11 A healthy 19 mm tweeter mounted for test.

Figure 15 shows the same plots for the 19 mm titanium sub-groups.

Figure 16 shows the same plots for the 26 mm aluminium sub-groups.

Figure 17 shows the same plots for the 26 mm titanium sub-groups.

Figure 18 shows the average on-axis THD result for the 19 mm aluminium control sub-group (19A0) with confidence intervals.

In order to minimize the length of this paper, all the remaining confidence interval plots, the frequency response measurement results off-axis and THD results are not included here. However, the move into the listening tests and further acoustical measurements was motivated by evaluation of the full measurement data.

It became clear that the sub-groups for which there was any statistically significant difference whatsoever was between sub-groups 19T0 (19 mm titanium control) and 19T2 (CrN/DLC thick coating) and 19T4 (Cr/CrN thick coating) sub-groups, with the largest different being to the 19T4 sub-group. The differences are seen in the frequency response data, both on and off-axis.

No certain differences were identified from the measurement data in any other sub-groups or for THD.

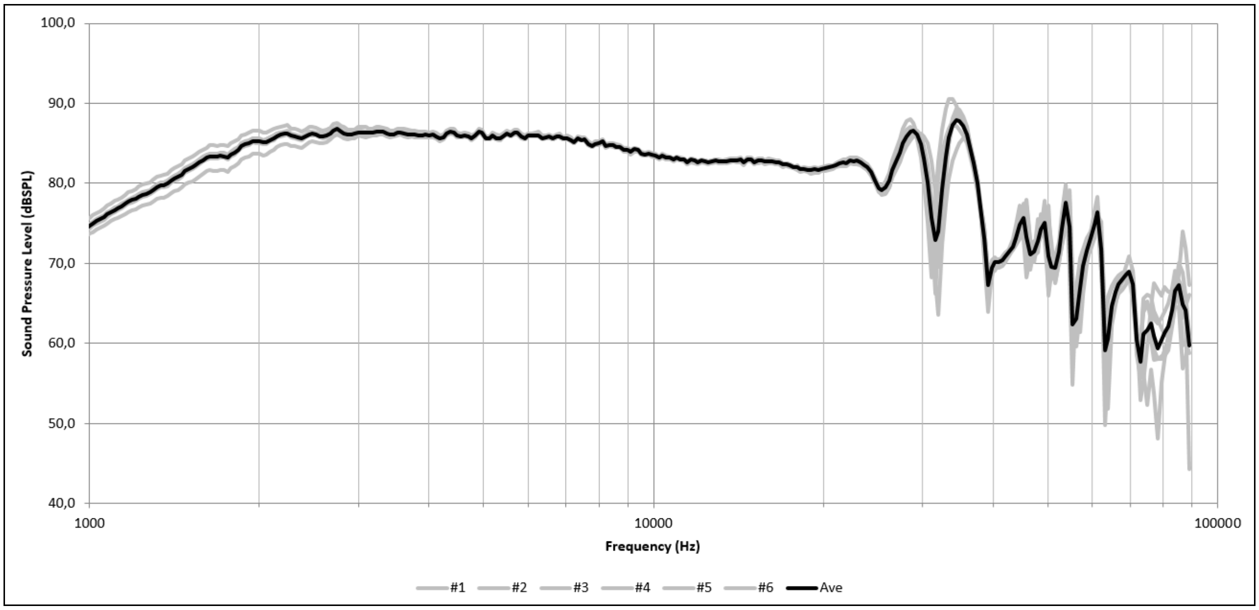

Figure 12 On-axis frequency response results for the 19 mm aluminium control sub-group (19A0).

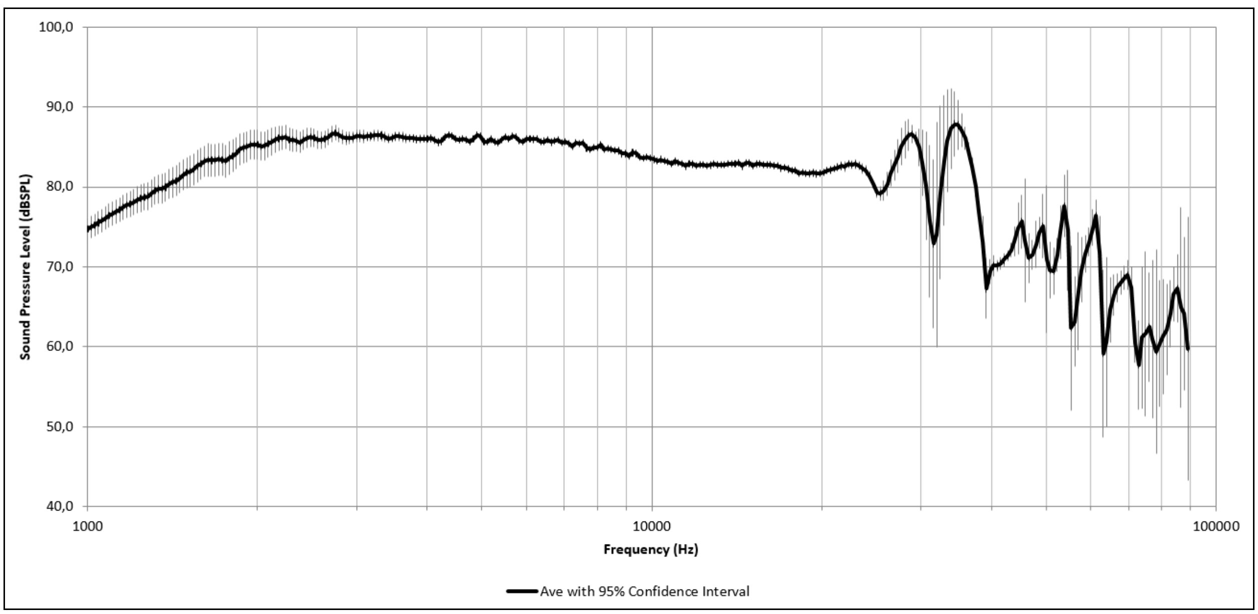

Figure 13 Average on-axis frequency response for the sub-group 19A0 with confidence intervals.

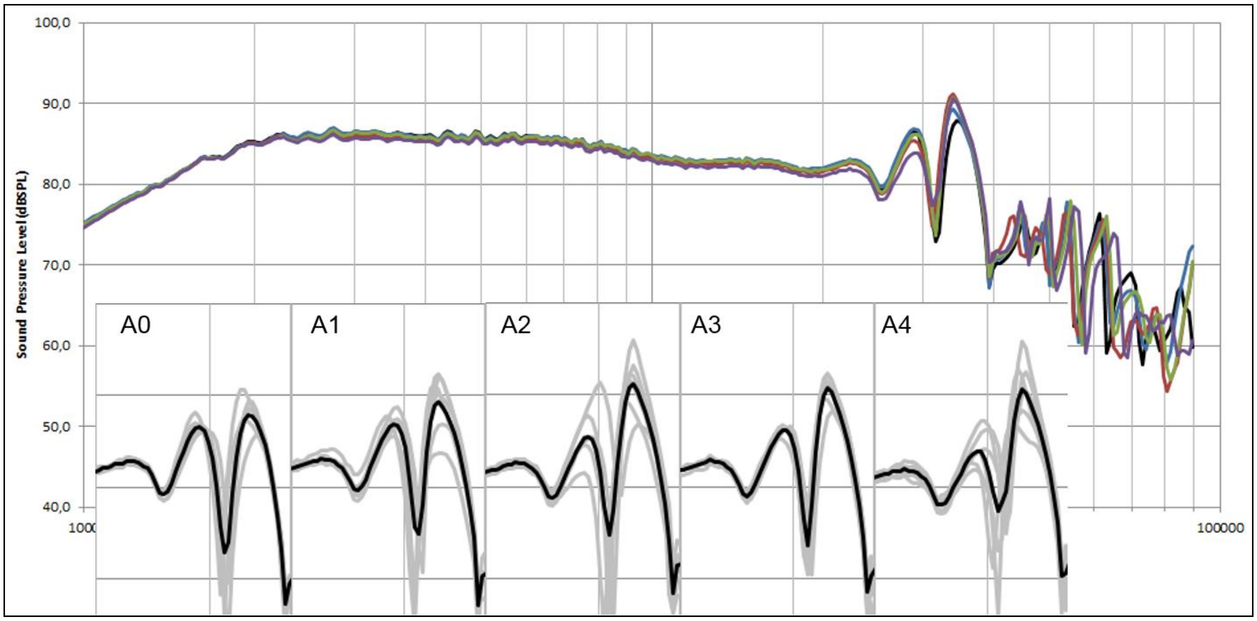

Figure 14 Average on-axis frequency response results for the 19 mm aluminium sub-groups with break-up insets.

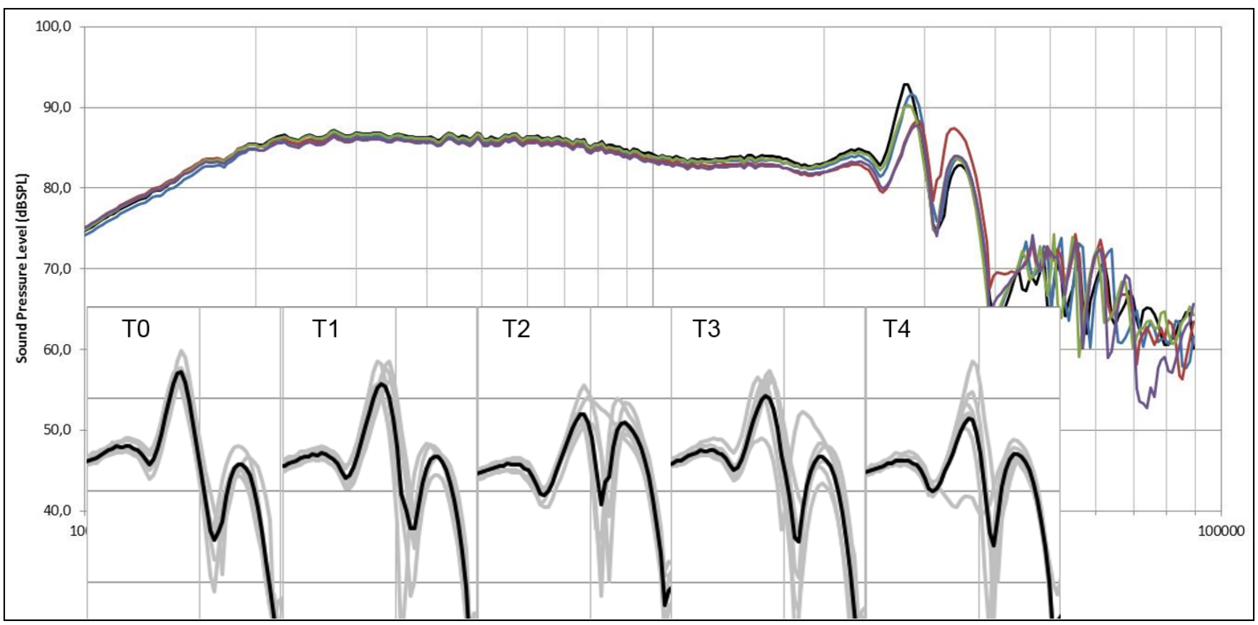

Figure 15 Average on-axis frequency response results for the 19 mm titanium sub-groups with break-up insets.

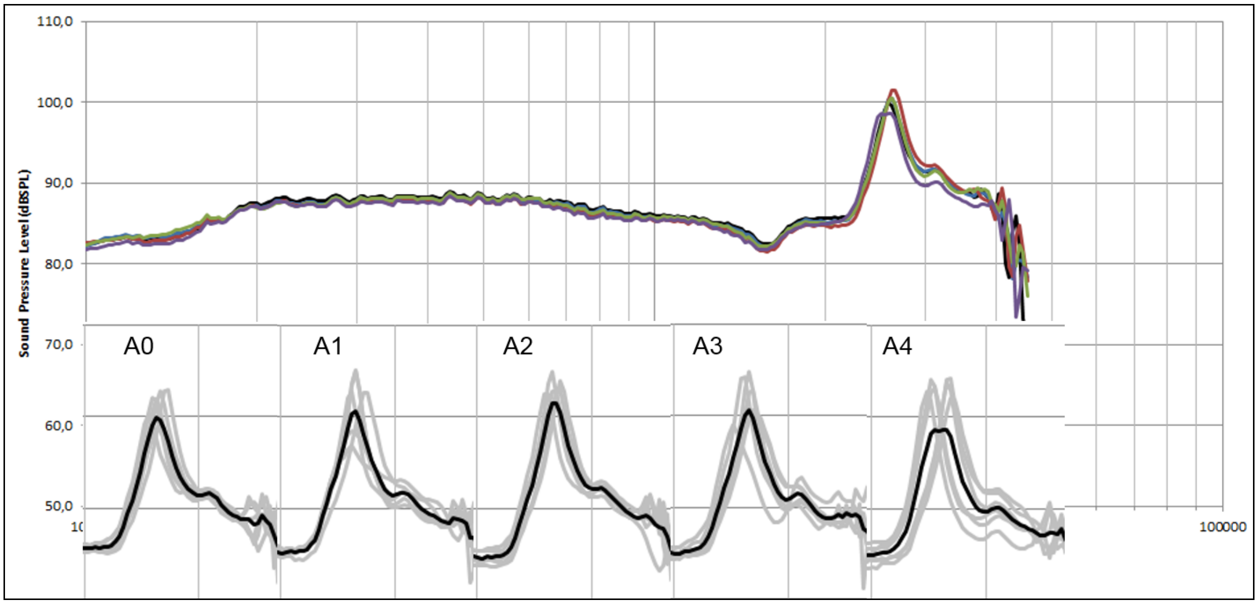

Figure 16 Average on-axis frequency response results for the 26 mm aluminium sub-groups with break-up insets.

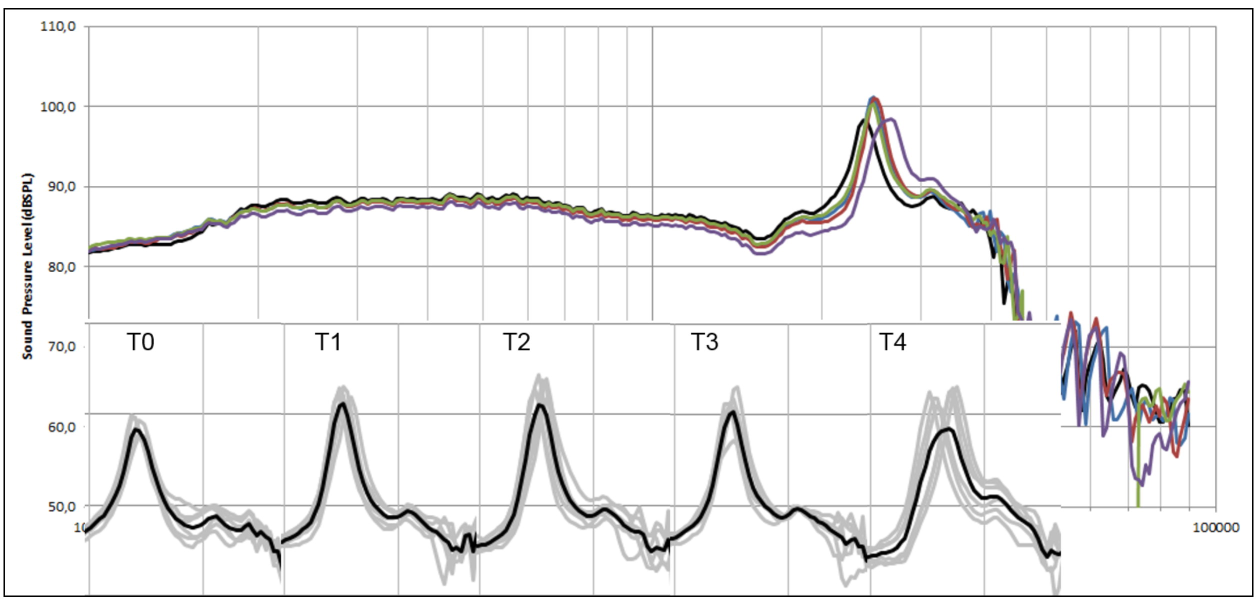

Figure 17 Average on-axis frequency response results for the 26 mm titanium sub-groups with break-up insets.

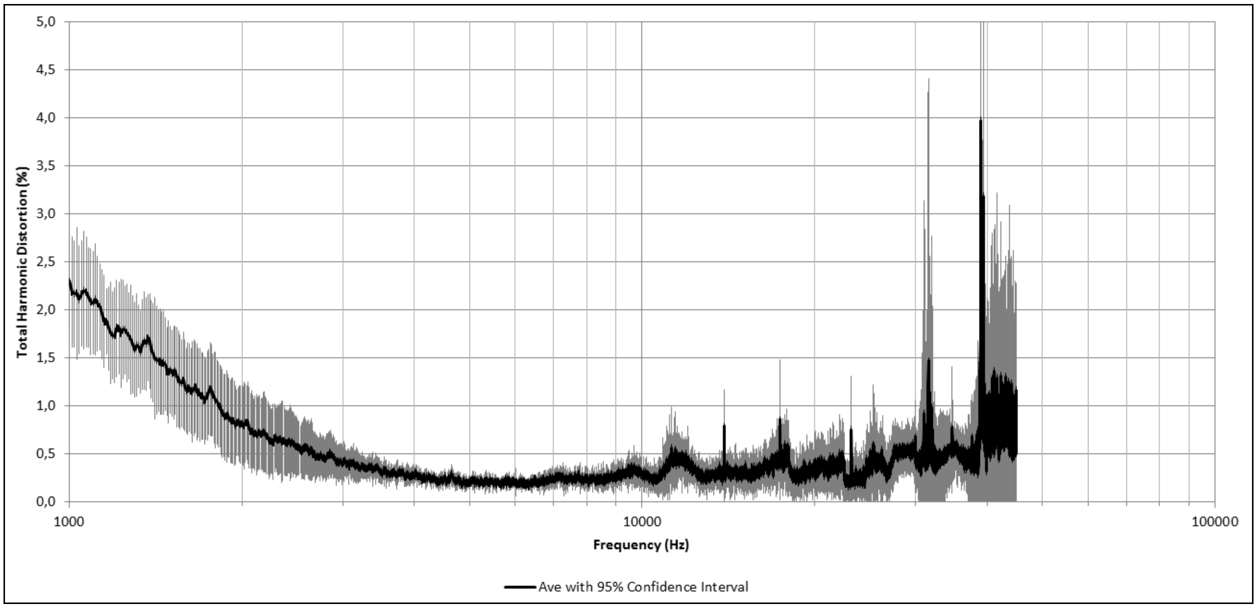

Figure 18 Average on-axis THD response for the control sub-group 19A0 with confidence intervals.

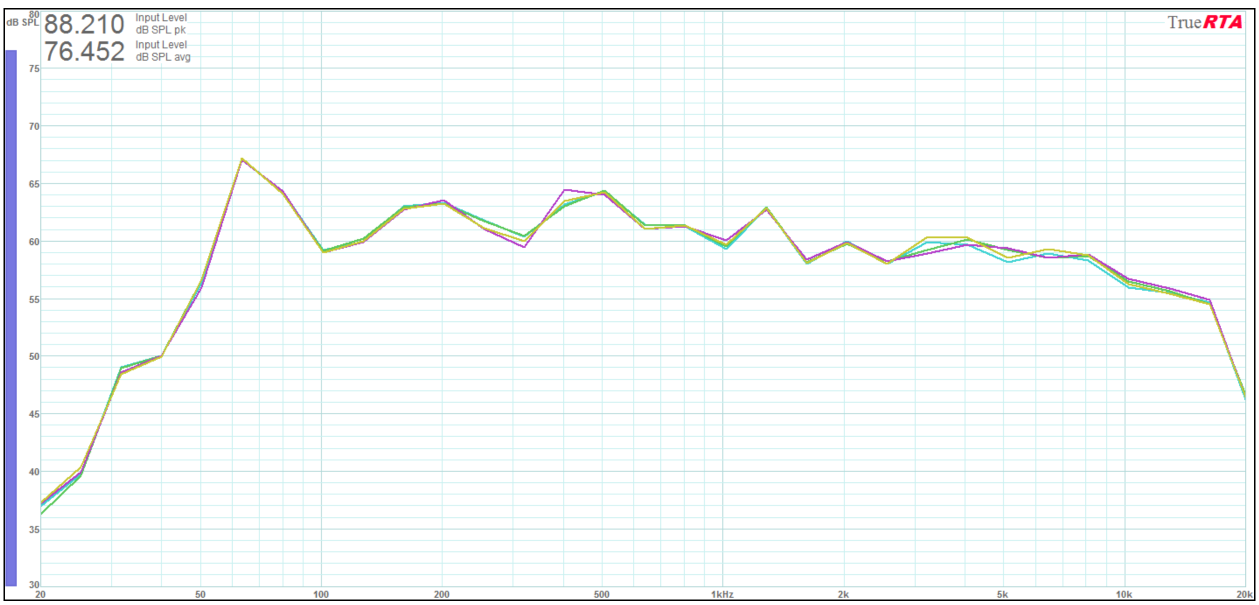

Figure 19 Listening position room responses in 1/3rd octaves for the system with each tweeter in both baffle positions.

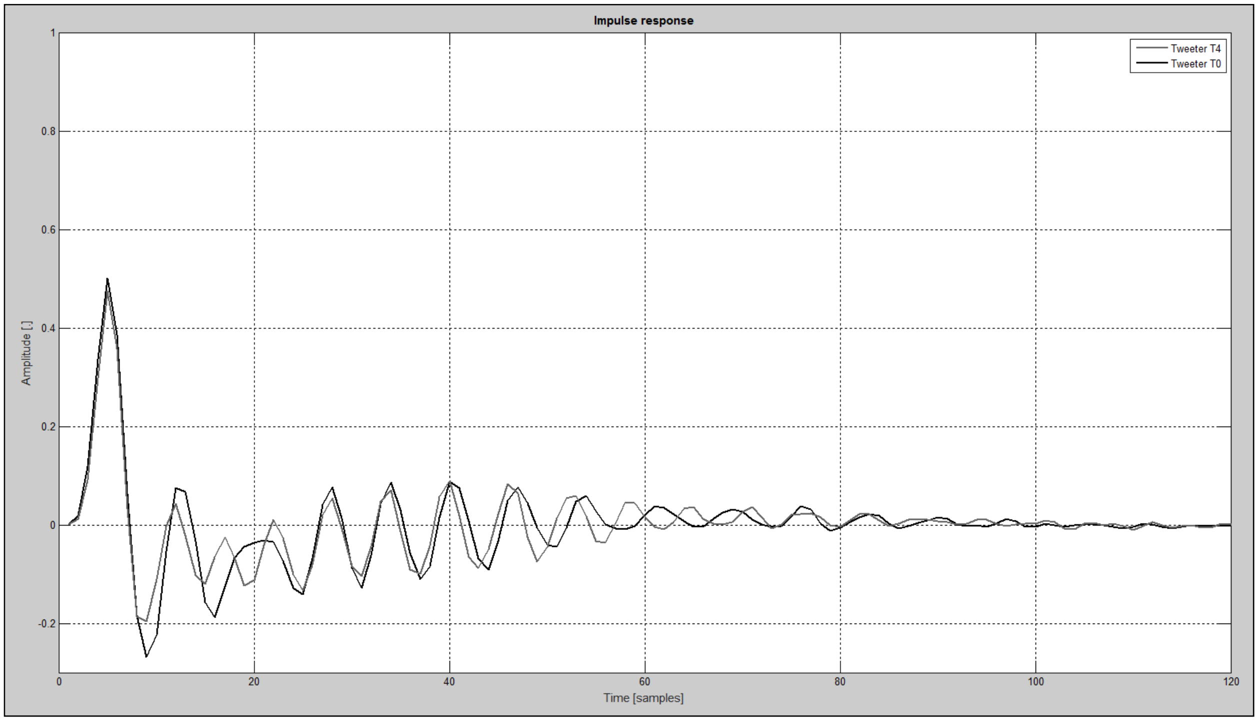

Figure 20 Impulse response of nominal (most average) tweeters from sub-groups 19T0 and 19T4 in listening tests.

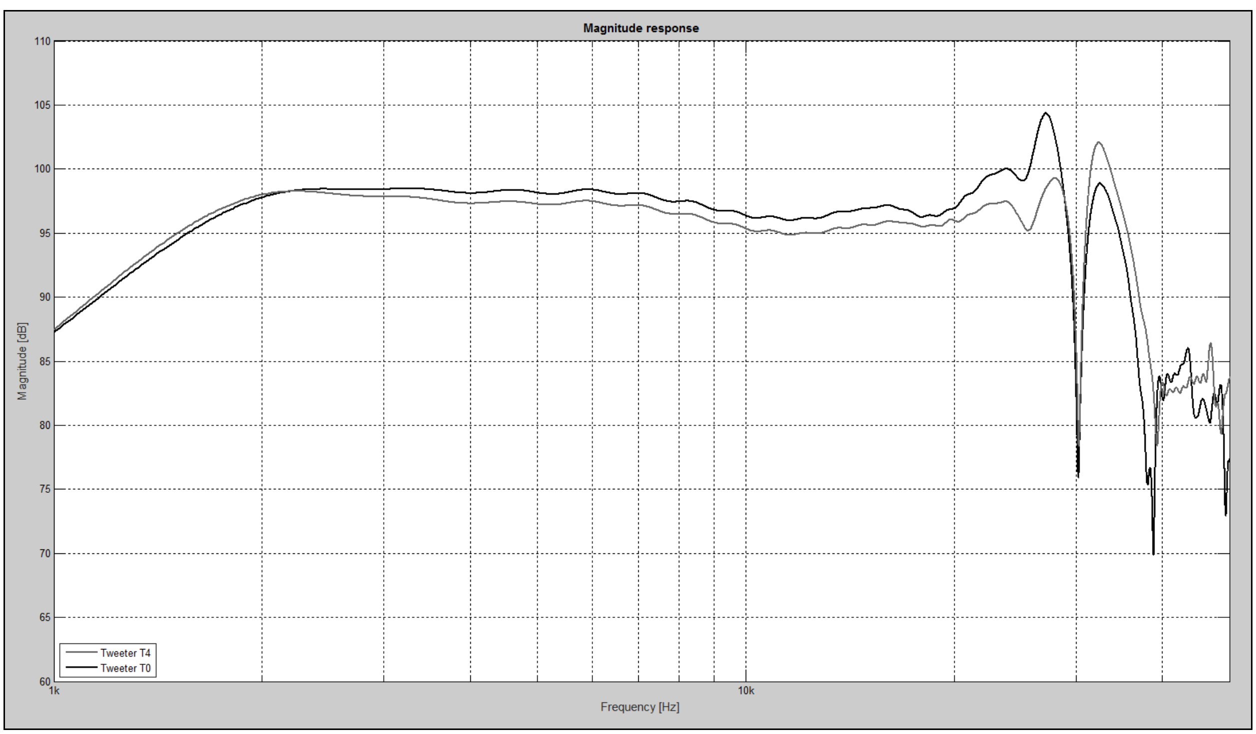

Figure 21 Frequency response of nominal (most average) tweeters from sub-groups 19T0 and 19T4 in listening tests.

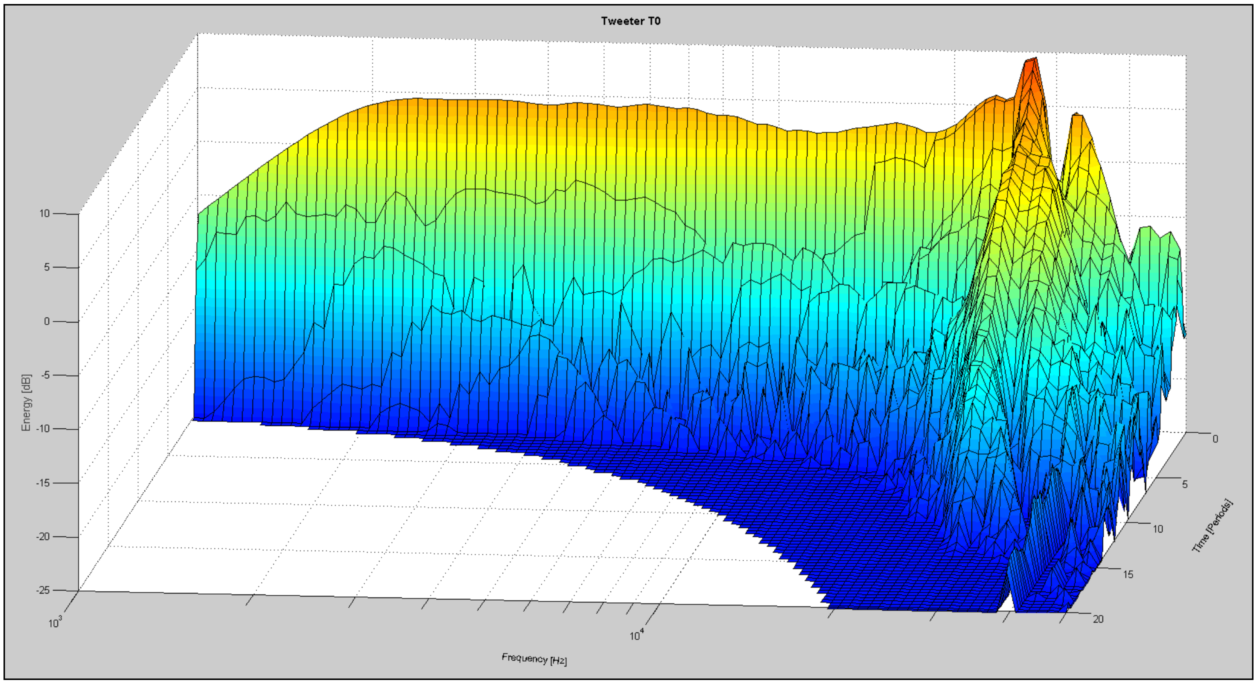

Figure 22 Waterfall plot of nominal (most average) tweeter from sub-group 19T0 used in listening tests.

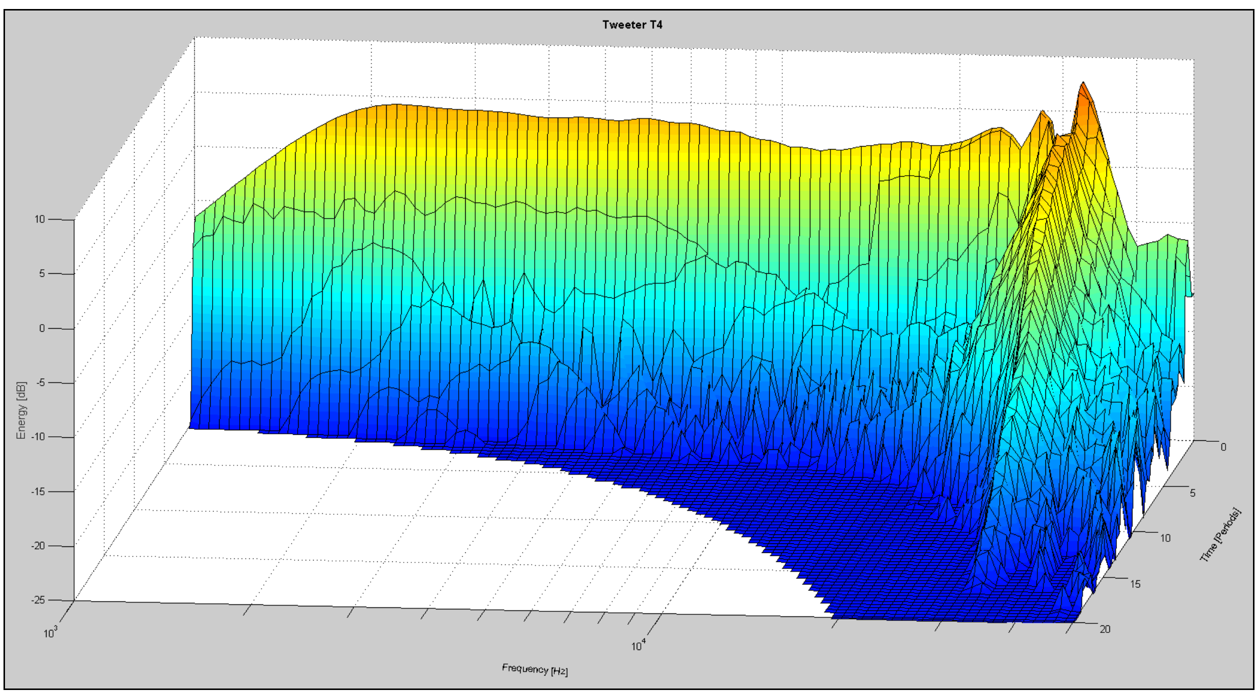

Figure 23 Waterfall plot of nominal (most average) tweeter from sub-group 19T4 used in listening tests.

6.4. Listening Test Results

The listening test described was executed with the two nominal (most average) tweeter units from the sub-groups 19T0 and 19T4. 18 listeners participated in two rounds of 9 listeners who each completed 36 tasks in the ABX test and the results were as follows:

- Round 1 correctly identified X = 87.3 %
- Round 2 correctly identified X = 81.8 %
- Overall correctly identified X = 84.6 %
- Lowest individual score = 52.8 %
- Highest individual score = 100 %

In this ABX type of test, a result of 50 % would mean the listeners are guessing or there is no audible difference and 100 % would mean no errors at all. The lowest individual score came from the oldest listener at 60 years. Five listeners identified X correctly in 35 or 36 out of 36 tasks. Four of these listeners were asked to repeat the test and indicate their subjective preference for A or B in each of the 36 tasks. The results were as follows:

- Overall preference for 19T4 = 52 %
- Lowest individual preference for 19T4 = 14 %
- Highest Individual preference for 19T4 = 83 %
- Overall consistency for same tweeter = 74 %

The overall preference for 19T4 of 52 % means that the preference for 19T0 was therefore 48 %. Interestingly, the overall consistency for choosing the same tweeter lies halfway between 50 % (equal or no preference) and 100 % (all listeners prefer the same tweeter in all cases).

Figure 19 shows the listening room responses in 1/3rd octaves for the system with each tweeter in both baffle positions. The four responses indicate differences in the range 3 to 8 kHz despite the two tweeters being identical in this range - apart from the sensitivity difference which has been compensated. In other words, the physical set-up of the tweeters in the baffle, additional speaker underneath and relation to the surroundings are influencing the response. It can be noted that reversing the positions of the tweeters also reversed the responses.

6.5. Further Acoustical Measurements

Figure 20 shows the impulse response of the nominal (most average) tweeters from sub-groups 19T0 (black) and 19T4 (grey) used in the listening tests. The data is sampled at 192 kHz.

Figure 21 shows the frequency response of nominal (most average) tweeters from sub-groups 19T0 (black and 19T4 (grey) used in the listening tests. These results compare exactly to the earlier frequency response data. The sensitivity difference of 1.0 dB in the range 4 to 12 kHz is apparent.

Figure 22 shows the waterfall plot calculated for the nominal (most average) tweeter from sub-group 19T0 used in the listening tests. Figure 23 shows the waterfall plot calculated for the nominal (most average) tweeter from sub-group 19T4 used in the listening tests. Both waterfall plots show time in periods relative to the plotted frequency. Therefore, the relatively long ridges or ringing seen in both plots at 28 and 32 kHz respectively have decayed approximately 30 dB in approximately 15 periods.

7. CONCLUSIONS

The study has paid particular attention to ensuring that differences other than those that could be attributed to the coatings applied have been removed from influence by carefully ensuring that these other influences are spread evenly across all parts. Furthermore, six parts in each sub-group have been analysed – which is contrary to single parts as has been the case in much of the previous literature on the subject. It is clear from the objective measurements and the spread of, for example, frequency response around break-up within sub-groups, that drawing conclusions about performance from single measurements of single units in nonsensical.

This study has presented results of coating one side of 19 and 26 mm aluminium and titanium tweeter domes with CrN/DLC and Cr/CrN coatings using the PVD process. These materials have far greater stiffness's than the substrates in question and rival the stiffness of other exotic materials such as Beryllium and Titanium Nitride. The coatings applied increased the thickness of the substrates dramatically (up to 48 %) which is far more than previous literature has documented – and indeed leads one to question the validity of other studies. Furthermore, the masses of the raw domes has been increased by up to 58 %. The increase in mass naturally has a negative influence on the sensitivity and also affects the low frequency high-pass characteristics of the loudspeaker. Following analysis of the full objective measurement data and subjective test results in this study, the following conclusions can be drawn:

- Sub-groups 19T2 and 19T4 showed significant* differences around break-up. These two groups had the thickest coatings on the thinnest substrate. The break-up frequency was observed to increase by approximately 500 Hz and the break-up appears damped. This was observed in the on-axis and 30 degree off-axis frequency response measurements.
- No significant* differences were identified for the other 19 mm, or any of the 26 mm sub-groups.
- No significant* differences were identified in THD measurements between any of the subgroups.
- No clear improvement can be seen in the waterfall plot of 19T4 compared to the control 19T0.

**Significant is applied here to mean that the confidence intervals between sub-group results were separated.*

The ABX listening tests provided somewhat surprising results on first impression as audible differences were not really expected. However, having participated in the tests it became clear that differences existed. Overall, X was correctly identified in 84 % of tasks. Upon discussion, it would appear that the physical test set-up and its influence of the room responses could be a reason for there to be a high number of correct scores.

In the preference tests it appears the answer is not clear-cut. Certainly, an overall preference for 19T4 of 52 % indicates that there is equal preference for both tweeters. Therefore, one could conclude, that in the given test, people could generally identify a difference but could not agree on if one was better than the other. Incidentally, music from CD was chosen for the test as this is a medium very widely available and the scientific evidence for audibility of sound above 20 kHz is non-conclusive. Certainly, logic would suggest that for a loudspeaker to be marketable, it should first and foremost provide a performance benefit people can hear.

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