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I.T. Telecomunicación (Sonido e Imagen)

"Product Sound Evaluation"

BACHELOR THESIS

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Contents

1. Introduction

There are two types of product sounds; intentional and consequential sounds. Intentional sounds are those who have been put there deliberately, with the intention to perform a specific function for a product. The function of these sounds is of a communicative nature, with which the product interacts with the user, mainly to inform that some process is being carried out by the product or that a process is completed. Examples of these sounds could be a microwave bell or the ring of a phone. Consequential sounds are not incorporated deliberately but are direct consequence of the sound emitted by the product during operation. These sounds are dependent on the shape, size and materials of the parts that compose the product. Examples of these sounds could be the sound emitted by a pneumatic hammer during or the sound emitted by the engines of a plane [3].

Previously, consequential sounds have always been considered as noise and the way to deal with them was to try to reduce them at maximum. If they were considered during the design process of the product, the only way to respond to them was trying to minimize them as much as possible, as apparently its only function is to annoy and detract value to the product [2], but it is not exactly like that. It is possible that in the beginning, when the first vacuum cleaner came on the market, no one expected any particular sound of a vacuum cleaner, as this sound was unknown to all. In this case such a loud noise would only cause discomfort to the user, but nowadays this situation is very different. People expect a certain sound of a vacuum cleaner and associate that sound with its ability to perform its function, moreover the sound intensifies and becomes sharper as we increase the power of the appliance, so in this particular case can be expected that people associate loud sound with power. Therefore a silent vacuum cleaner can be considered as not too apt to play its role.

In product sound design these consequential sounds are treated not like noise that must be minimized at all costs, but as sounds that give personality to the product and influence the people’s perception of it. Therefore it will be taken into account how the design conditions interfere in the sound generation of the product, from the very moment of the prototype design. Being able to control the emitted sound allows the manufacturer to obtain greater control over the final product [2]; it allows him to try to turn that unwanted and unexpected mechanical noise in a feature that increases the value of his product. It also gives him the possibility to adapt the sound of his product to a specific type of customers.

The practice of product sound design is relatively new within the field of product development. This discipline, which has become relevant in the late 1990s, is not an easy task. We should not forget the fact that to change the mechanical noise of a product involves changing the mechanics of it. The components which are part of an appliance usually are designed to perform a specific function inside it. To try to control the emitted sound during the operation of the appliance without compromising the ability to perform the function inside the product of his components becomes a hard task. That is one of the reasons why product sound design requires an interdisciplinary approach. This process involves knowledge from very diverse areas as engineering, acoustics, psychology, psychoacoustics, sociology and musicology. That is why usually it requires working groups composed of specialists in the various mentioned areas to achieve meaningful results [3].

The design process begins by finding the desired sound or target sound for the product. This is usually carried out through an assessment of the sound generated by products of the same type as the product for which that target sound is wanted [3].

During this sound evaluation process two aspects are simultaneously studied: the way how people respond to the sound of the products and the physical parameters that compose these sounds. Through psychoacoustic analysis methods it is about to isolate and translate these impressions that the sound causes in people to physically measurable features within the sound spectrum. These physical parameters are classified as desirable or undesirable for the product and they will determine, to a greater or lesser extent, the physical characteristics that the target sound should have. This assessment is not simple at all, in the words of Lyon; “the difficulty comes from the quantification of the ambiguous customer's needs” [6].

After obtaining the target sound it is about to adapt the pieces that are part of the product with the intention to produce a sound as close as possible to the target sound. Feasibility studies are needed to know what features of the target sound can be incorporated into the design of the product and at what cost, and also to what extent these design conditions of the pieces affect the operation of the product [3].

This study focuses on product sound evaluation as a part of the product sound design process. Within the scope of a small study it will seek to clarify which physical characteristics would be desirable to find within the spectrum of the sound of a hairdryer for household use.

Three hairdryer models for domestic use of medium high end segment were chosen for the project. The main selection criterion for the three models was that they had the same retail price. The maximum price difference between models was 2 €.

The study focuses on two fronts: a sensory evaluation was conducted to find out how the public respond to the sound of these hairdryers and a psychoacoustic analysis of the spectrum of the sound was carried out in order to analyze its parameters. Both, the sensory evaluation and the psychoacoustic analysis of the sound are described in more detail in their respective sections. Formerly recordings of the hairdryers were performed in a semi-anechoic chamber to be used in both phases of the project.

2. The recordings

Recordings of the hairdryers were conducted to be used in subsequent phases of the project. The recordings were done in the semi-anechoic chamber of the Technische Universität Berlin. This chamber has a cut-off frequency of 250 Hz. These recordings were carried out with an artificial head measurement system and the software HEADrecorder, both products of HEADacoustics®.

The hairdryers were placed at a distance of 20 cm from the artificial head with an inclination of 45 ° from vertical and in an equidistant position to both ears, as shown in the picture. Three recordings were performed, one for each model, with 120 seconds in length. The hairdryers were recorded at their maximum power.

Fig. 2.1. Recording of hairdryer 2 with artificial head recorder in semi-anechoic chamber in Technische Universität Berlin.

It was considered the possibility of making these recordings in a dynamic manner, imitating the movement that makes a person while using a hairdryer, but there were two problems: first, the way of drying your hair is quite different depending on the length of the hair and the hairstyle that the person wears, so it would have been difficult to determine a standardized way to dry your hair. Moreover, I would like to highlight the fact that maintaining the hairdryers during the recordings statically implies that there is no possibility of interference in the results by the person responsible of the emulation of these movements. Furthermore, there was also the problem of the sound absorption provided by this person; it would have directly interfered in the results of the measurements.

The fact of having carried out the recordings of the hairdryers in a static position has greatly facilitated the analysis of the psychoacoustic parameters of the sounds, since the sound does not show changes over time.

All graphics referring to sound spectrum analysis which appear in this study are a direct result of the analysis of these recordings. They were also used to conduct the interviews and the semantic differential test described in the section about sensory evaluation.

3. Psychoacoustic analysis of the sound

This section provides a brief description of the psychoacoustic parameters analyzed in the sound of the hairdryers and the mathematical models that have been used to do it; according with the models of Zwicker and Fastl [1]. This analysis was performed on the recordings of the hairdryers that were made in the semi-anechoic chamber of the University. The analysis was conducted with HEADAnalyser Artemis v12.01 software by HEADAcoustics ®.

3.1 Loudness

Loudness is a sound sensation which belongs to the category of intensity sensations. Through this parameter sounds can be classified on a scale ranging from less intense to the most intense. Therefore, loudness depends on the sound pressure level and its frequency, length and spectral complexity [13].

The sound pressure level, which is a physical attribute, is linked to loudness sensation, but two tones with equal sound pressure level but different frequency will produce different loudness sensation, since the human ear does not respond with the same sensitivity over the entire range of frequencies [13].

The measurement procedure is subjective; the listeners have to make judgments according to known sound pressure levels, which were taken as a reference [13].

To represent the level of sensation perceived taking into account both, sound intensity and frequency, a new physiological magnitude is introduced: the loudness level (LN). Its unit is phon. Loudness level of a sound is the sound pressure level of a 1 kHz tone in a plane wave and frontal incident that is as loud as the sound. This concept was introduced by Barkhausen in the twenties, to characterize the sensation of loudness of any sound [13].

Through standardized tests the isophonic map of the audible field was obtained, with his curves representing states with the same level of loudness sensation.

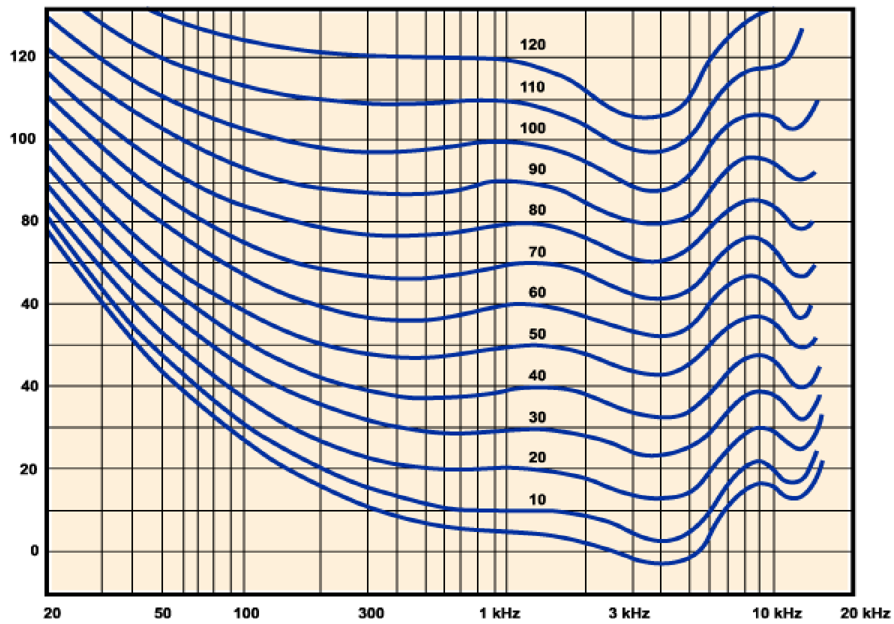


Fig. 3.1. Isophonic map. [ISO-532]

As seen in the chart above, equal loudness curves converge at low frequencies but between 1 kHz and 10 kHz are substantially parallel. It can also be seen that the ear presents maximum sensitivity between 1 kHz and 4 kHz, also that the ear responds poorly to low and high frequencies [13].

The equal loudness contours shown are for a sound field with frontal incidence. However, it may happen that the sound field is similar to what is known as diffuse field, when the sound comes from all directions for example. Our hearing system is not equally sensitive to sounds that come from different directions, and this direction dependence in turn also depends on frequency. Therefore, equal loudness curves are different for free and diffuse field. This difference can be expressed as the attenuation required to produce equal loudness in free and diffuse field. At low frequencies this attenuation is negligible, since our hearing system responds as an omni-directional receiver to these frequencies, but we would find a -3dB attenuation for a frequency around 1 kHz in a diffuse field for example [13].

As loudness level is measured on a relative scale, there is no linear relationship between the sensation intensity and the magnitude value; for example an increase of 10 phons in the lower loudness zone is perceived as a six times increase of the apparent loudness sensation, while the same increase in a higher zone, from 50 to 60 phones, is perceived as double loudness sensation. It is necessary to define a scale of sounds to establish a linear relationship between the value of the scale and the perceived loudness sensation. A new magnitude appears to solve this problem: loudness (N), its unit is sone. One sone is the loudness of 1 kHz pure tone with 40 dB sound pressure level [13].

Both magnitudes, sone and phon are related with each other as follows:

$$S = 2^{\left(\frac{phone-40}{10}\right)}$$

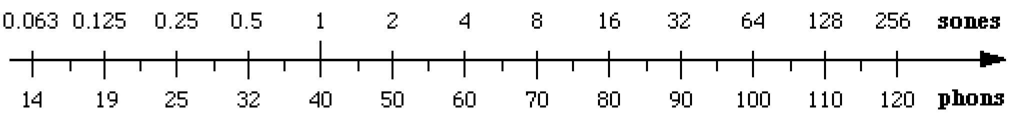


Fig. 3.2. Relation between sones and phones.

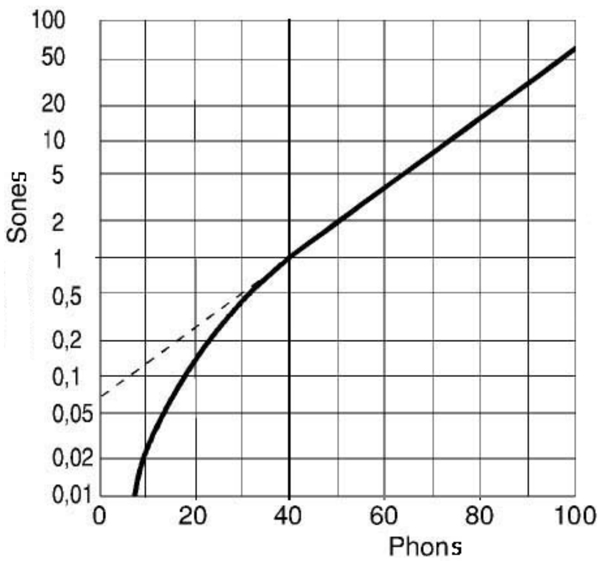


Fig. 3.3. Relation between sones and phones, As can be seen there is a constant relationship between loudness and loudness level for values over 40 phons.

This method for the obtaining of standardized loudness is only valid for pure tones. Complex sounds are perceived by the ear as if they were louder. There are a big amount of effects that must be taken into account when we try to analyze loudness in complex sounds, which makes the evaluation of loudness much more complicated. Loudness sensation is increased when the bandwidth of the frequencies that compose the sound increases [13].

3.1.1 Loudness model

The method used for the analysis of loudness is the method of Zwicker (ISO-532B) [1]. This method requires a spectral analysis of the sound; the analysis is carried out for third octave bands. The reason for which the analysis is performed for third octave bands is due to the behavior of the human hearing and his critical bands [13].

The method is standardized as a graphic procedure in which from the sound pressure levels measured for each third octave band a specific loudness is assigned (loudness per frequency unit: Son / Bark). Subsequently total loudness can be calculated as the area under the plotted curve [13].

To carry out its calculation it is required a set of ten charts, by which loudness levels are assigned based on the measured sound pressure levels. These charts are provided by the standard ISO 532B, UNE 74014-78, an example of these charts can be seen in the figure below. Charts 1 to 5 are used in case of free sound field conditions and the charts from 6 to 10 in diffuse field. The abscissa axis shows the critical bands of the ear. These critical bands are approximately third octave in the range between 280 Hz and 14 kHz. For frequencies below 280 Hz the critical bands are larger than third octave. Therefore, the bands 45 to 90 Hz, 90 to 180 Hz and 180 to 280 Hz range 4, 3 and 2 octave bands respectively. The ordinate axis shows the sound pressure levels for each band [13].

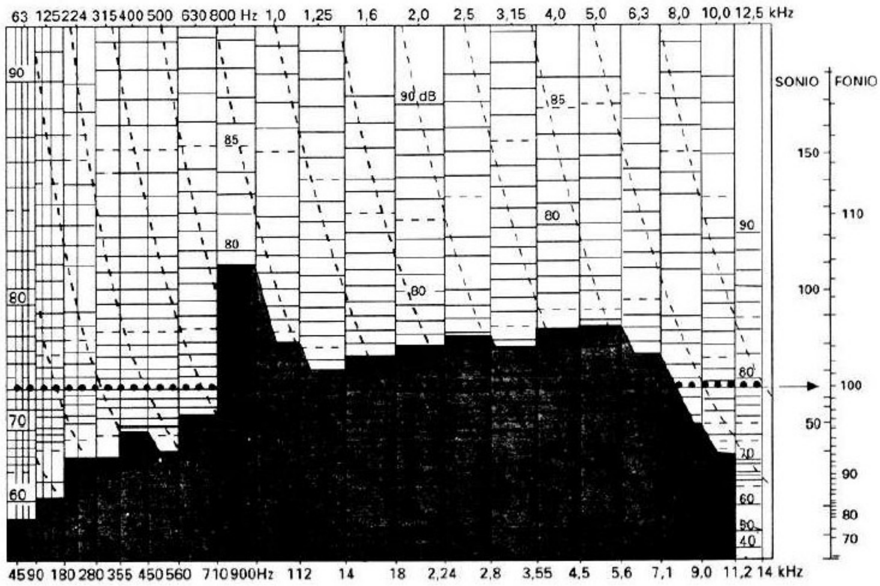


Fig 3.4. Example of one of the 10 charts provided by the standard for loudness calculation. [ISO 532B, UNE 74014-78]

The method assumes that the band with more loudness produces an asymmetric masking, i.e. that the band with more loudness masks the higher frequency bands in a more forceful way than lower frequency bands. Furthermore it masks in a different way the bands that have his central frequency close to the central frequency of the masking band. This causes a decrease in the contribution from these masked bands for the calculation of total loudness [13].

These are the steps to be followed to calculate loudness using this method [13]:

- Select the appropriate chart depending on the type of sound field (free or diffuse) and identify the highest sound pressure level among the measured bands.

- Draw the sound pressure levels measured in third octave bands on the chart with horizontal segments. As for frequencies below 280 Hz the critical bands are larger than third octave, the sound pressure level for each one of this critical bands is calculated as the sum of the quadratic sound pressure levels of the third octave bands which are included into this critical bands.

- Join by a line each two consecutive band levels.

- If the level of a band is smaller than the level of the next band (higher frequency), both are joined together by a vertical line on their common abscissa, which is equivalent to assume that there is no masking towards lower frequencies.

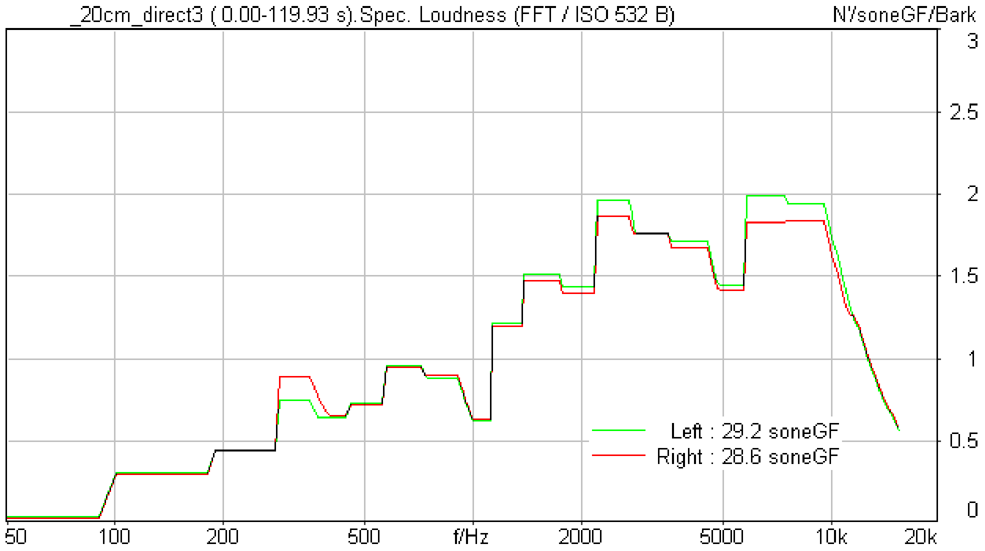
- If the level of a band is higher than the level of the next, a decreasing curve is plotted, whose starting point is the right edge of the higher level following the described trend by the adjacent dashed lines drawn on the chart. These lines show the pattern of the masking effect of each band over the upper frequency band.

- The figure obtained is transformed into a rectangle with a base equal to the entire represented band and an area equal to the original figure. The height of the resulting rectangle gives the total loudness level (phon), or total loudness (sone) according to the graph scales that appear on both sides of the chart.

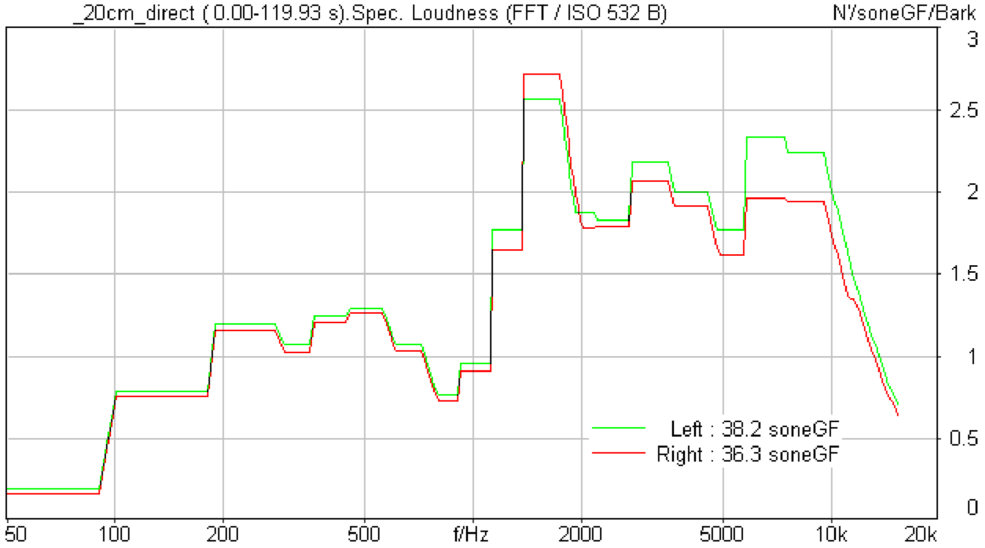
3.1.2 Results

The results of loudness analysis of the three hairdryers for left and right channels are shown below.

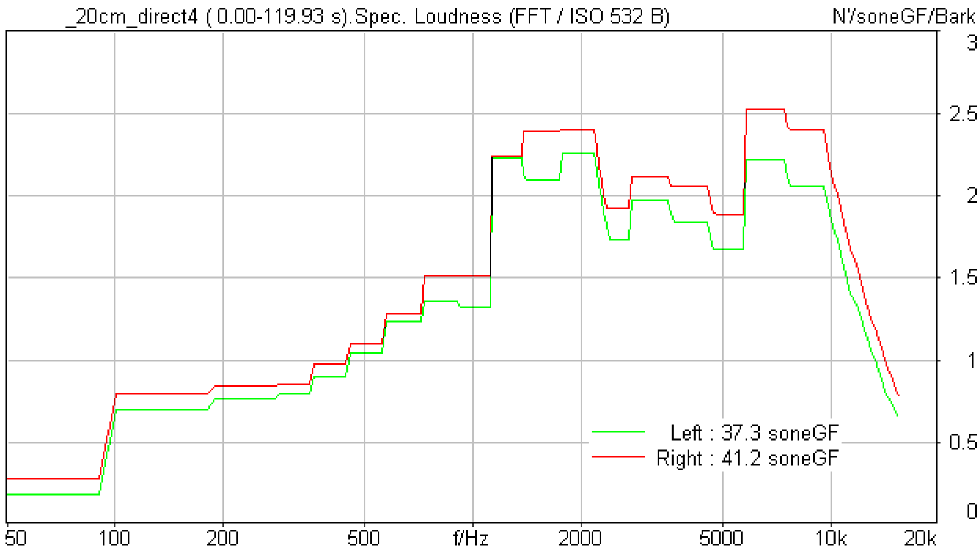
Hairdryer 1



Hairdryer 2



Hairdryer 3



3.2 Sharpness

Sharpness is basically a measure of the high-frequency content of a sound. This parameter is associated with the sensation of sound density. The density is a feature that makes it possible to distinguish two sounds with equal intensity and fundamental frequency emitted by different sources. This parameter describes the perception of sound as dull or sharp [13].

According to the Zwicker's method [1], sharpness (S) is given by the following equation, its unit is acum.

$$S = 0'11 \frac{\int_{z=0}^{24} N'(z) \cdot g(z) \cdot z \cdot dz}{N}$$

The coefficient of the expression that defines the sharpness is set to 0'11 to normalize the result so that a signal with a central frequency of 1 kHz and 60 dB of sound pressure level and a bandwidth lower than one critical band will have a sharpness value equal to 1 acum [1].

In this equation, S is the sharpness to be calculated and the denominator gives the total loudness N. The upper integral is like the first moment of specific loudness over critical-band rate, but uses an additional factor, g(z), that is critical-band-rate dependent [1].

This factor is shown in the picture below as a function of critical-band rate. Only for critical-band rates larger than 16 barks does the factor increase from unity to a value of four at the end of the critical-band rate near 24 barks. This takes into account that sharpness of narrow-band noises increases unexpectedly strongly at high centre frequencies. Accordingly, for a sound in which does not appear loudness above 16 barks, sharpness will be proportional to the position of the center of gravity of the spectrum. But if the loudness is above 16 barks sharpness will be strongly increased [1].

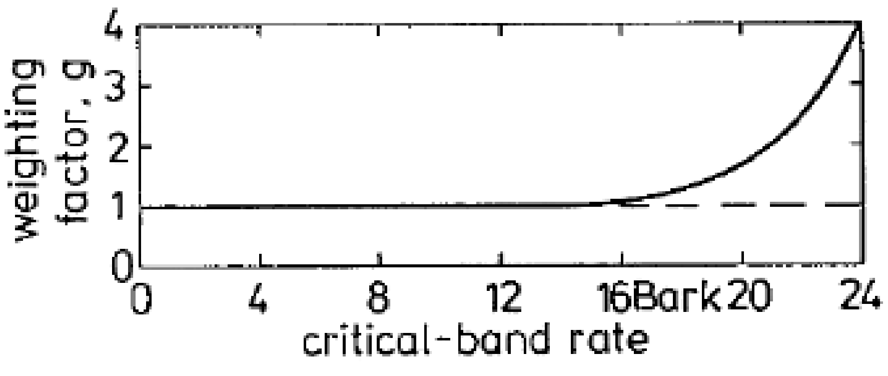


Fig. 3.5. Weighting factor for sharpness as a function of critical-band rate [1]

3.2.1 Sharpness model

The model of Aures [ISO-532B] has been chosen mainly for calculating sharpness. This method introduces some changes over the predecessor model proposed by Von Bismark.

Von Bismark developed a procedure for the sharpness calculation based on the distribution of specific loudness through the critical bands [13]:

$$S_B = c_B \frac{\int_0^{24 Barks} L(z) \cdot g(z) \cdot dz}{\int_0^{24 Barks} L(z) \cdot dz}$$

L(z) is the loudness per critical band; g(z) is the weighting function; c_B is a constant that should be determined empirically, and serves to adjust the result to make an arbitrary sound to have a value of one unit of sharpness, this means that the sounds evaluated through this method will have their sharpness values relative to this arbitrary sound.

Aures method makes sharpness dependent on total loudness [13]:

$$S = 0'11 \frac{\int_{z=0}^{24} N'(z) \cdot g'(z) \cdot z \cdot dz}{\ln\left(\frac{N+20}{20}\right)}$$

$g'(z) = 0'066 \cdot e^{0'171 \cdot z}$ is the weighting function of Aures, which takes this value above 16 Barks and $g'(z) = 1$ under 16 Barks.

The constant at the beginning of the expression is set to 0'11 to normalize the result so that a signal with a central frequency of 1 kHz, 60 dB of sound pressure level and bandwidth smaller than one critical band has a sharpness value equal to 1 acum.

3.2.2 Results

The results of sharpness analysis of the three hairdryers using the Aures method are shown below.

Hairdryer 1

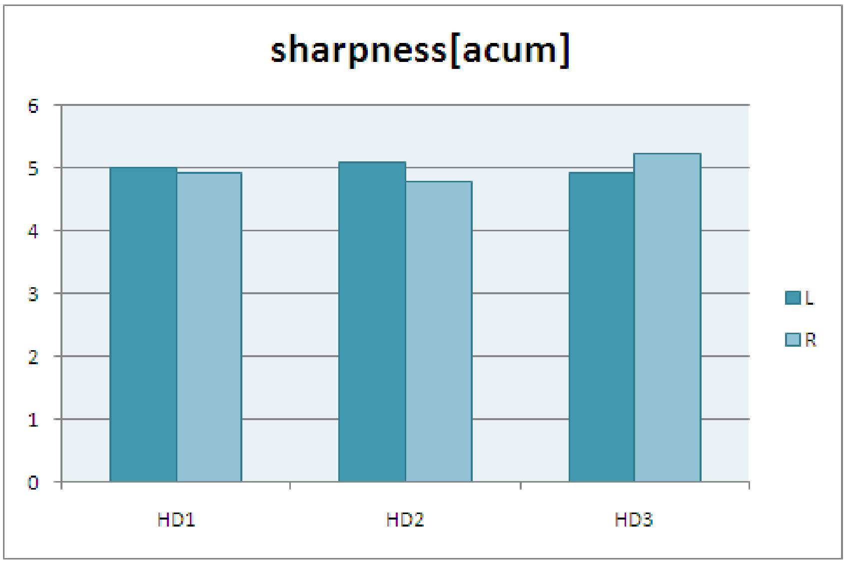
- *Left channel: 5,01 acum*
- *Right channel: 4,91 acum*

Hairdryer 2

- *Left channel: 5,09 acum*
- *Right channel: 4,79 acum*

Hairdryer 3

- *Left channel: 4,91 acum*
- *Right channel: 5,23 acum*



3.3 Roughness and fluctuation strength

These parameters are an attribute related to the subjective perception of stationary noises into the sound. They are determined by the frequency and amplitude of modulation of these stationary noises [13].

Roughness and fluctuation strength sensation appears when amplitude fluctuations occur. There are three different feeling regions, depending on the frequency of modulation of this signal [13]:

- At very low modulation frequencies periodical variations of loudness are perceived, this sensation reaches a maximum for modulation frequencies around 4 Hz and decreases for higher frequencies. Up to 20 Hz the ear is able to perceive this loudness variation; this sensation is called fluctuation strength.

- From 15 Hz appears what is called roughness, which increases with frequency, reaching a maximum sensation close to the frequency of 70 Hz, it is slightly dependent on the central frequency. The spectrum of the modulation function must be between 15 and 300 Hz to produce roughness. For this reason, usually the narrowband noises sound rough, even when periodic changes in the envelope do not appear. This sensation may not only arise from modulations in amplitude, but it can also be produced by modulations in frequency or phase.

- From 70 Hz roughness sensation decreases again, and the sensation of perceiving three different tones starts to increase (two of them produce this loudness periodical variations and a nonexistent tone associated with the modulation frequency).

Roughness unit is asper, one asper is equivalent to the sensation produced by a tone with 60 dB sound pressure level and 1 KHz as a central frequency, with a modulation frequency of 70 Hz modulated at 100% of amplitude. If the modulation is on frequency, the parameters which should be taken into account are frequency and rate of modulation [13].

Fluctuation strength unit is vacil, and it is defined as a 1 KHz and 60 dB tone modulated at 4 Hz with a modulation rate equal to 1.

Ernst Terhardt was one of the main responsibles for defining the limits and causes of roughness. In his research, he noticed that both frequency and amplitude modulations cause roughness, and also that the main physical parameters related to roughness are amplitude and frequency of modulation. He found that for amplitude modulations a double sensation of roughness is perceived when a variation of 40 dB is given [13].

Some years later, Kemp studied the specific influence of frequency modulated tones and the results were similar to those of Terhardt. He found that the influence that sound pressure level exercises on this type of modulation is equal to three times roughness sensation for the same 40 dB variation [13].

Aures developed a procedure to calculate roughness from the sum of the partial values of roughness versus the number of critical bands [13]:

$$R = 52'3\sum_{i=1}^{24} r_i \cdot \Delta z \frac{(k_{i-1} + k_i)}{2}$$

The term $\frac{(k_{i-1} + k_i)}{2}$ represents the significance of the correlation factors between the temporal envelopes of two band-pass functions which belong to two adjacent critical bands.

The 52'3 value was chosen to normalize the result.

3.3.1 Roughness and fluctuation strength model

The following equations show the models used for roughness and fluctuation strength calculation, both models of Zwicker [1]:

$$R = 0'3 \cdot \frac{f_{\text{mod}}}{kHz} \int_0^{24} \frac{\Delta L_E(z)dz}{dBBark}$$

$$F = 0'008 \cdot \frac{\int_0^{24} \frac{\Delta L}{dBBark} \cdot dz}{\frac{f_{\text{mod}}}{4Hz} + \frac{4Hz}{f_{\text{mod}}}}$$

ΔL is the difference between maximum and minimum levels of the signal envelope in critical bands.

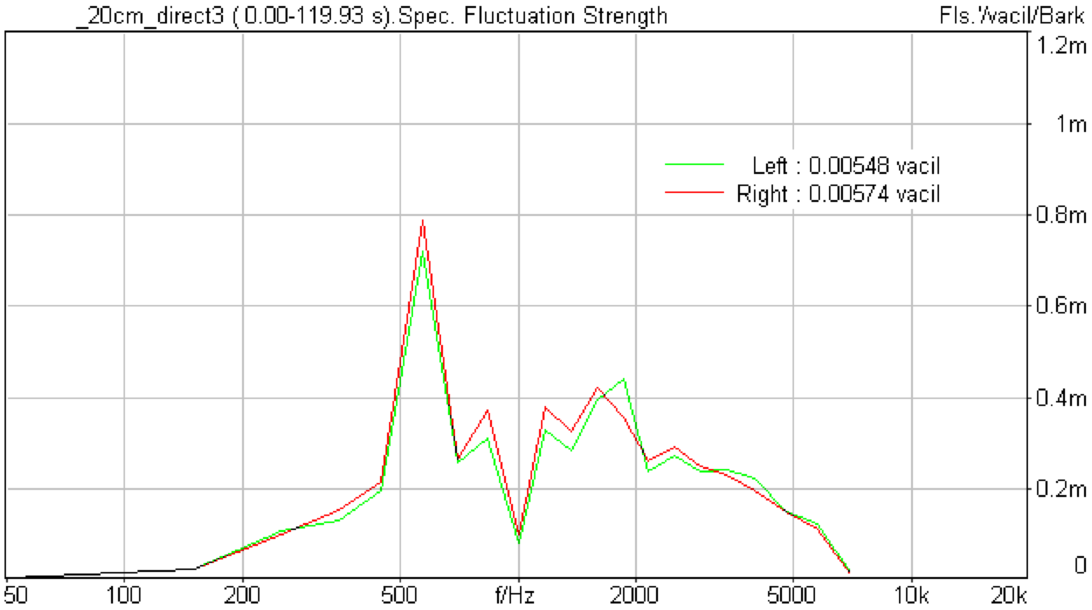
f_{mod} is the modulation frequency.

0.3 and 0.008 values were chosen experimentally to normalize the result.

3.3.2 Results

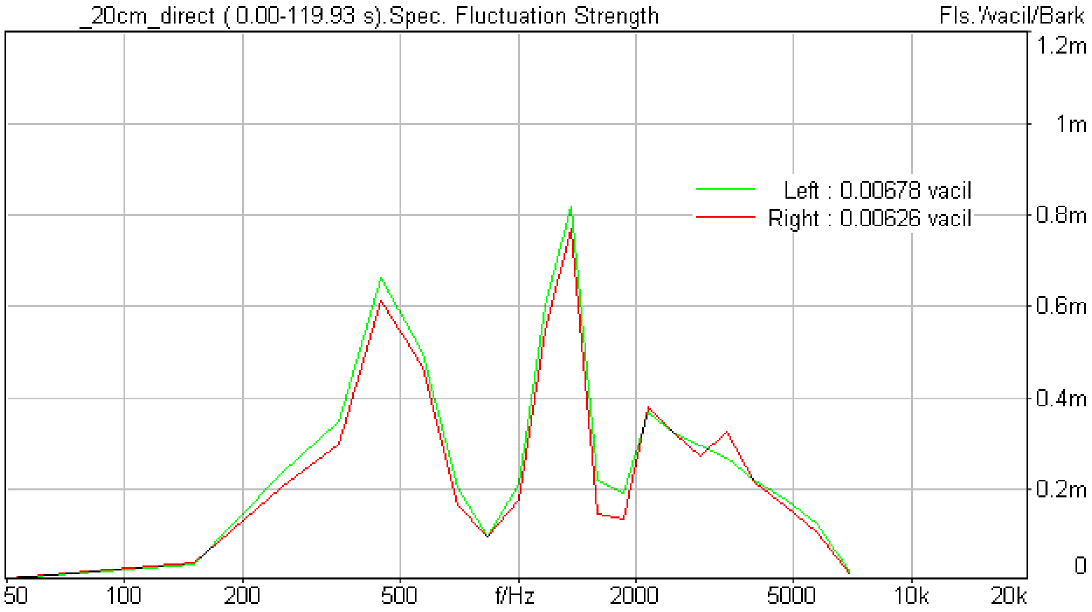
The results of roughness and fluctuation strength analysis of the hairdryers for both left and right channels are shown below.

Hairdryer 1

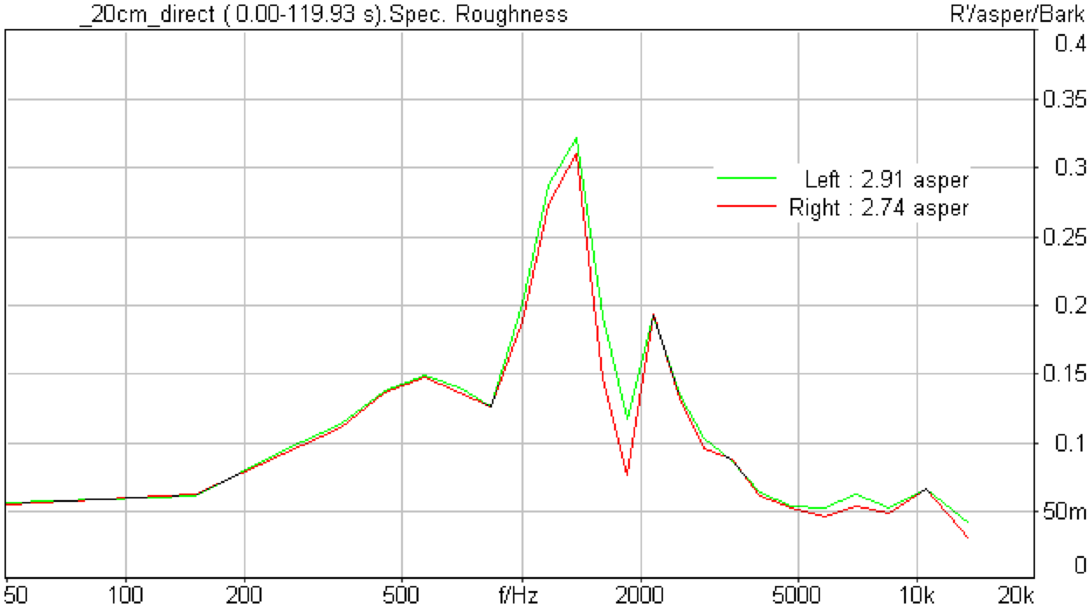

_20cm_direct3 (0.00-119.93 s).Spec. Fluctuation Strength
Fls.'/vacil/Bark
Left : 0.00548 vacil
Right : 0.00574 vacil
1.2m
1m
0.8m
0.6m
0.4m
0.2m
0
50
100
200
500
f/Hz
2000
5000
10k
20k


_20cm_direct3 (0.00-119.93 s).Spec. Roughness
R'/asper/Bark
Left : 2.37 asper
Right : 2.38 asper
0.4
0.35
0.3
0.25
0.2
0.15
0.1
50m
0
50
100
200
500
f/Hz
2000
5000
10k
20k

Hairdryer 2

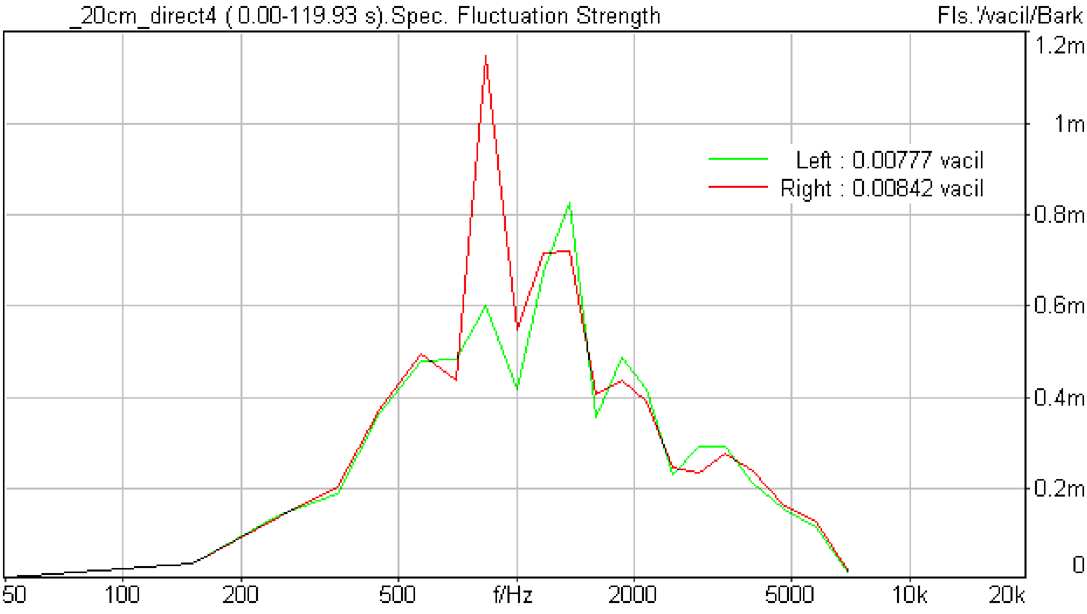


_20cm_direct (0.00-119.93 s).Spec. Fluctuation Strength
Fls.'/vacil/Bark
1.2m
1m
0.8m
0.6m
0.4m
0.2m
0
Left : 0.00678 vacil
Right : 0.00626 vacil
50
100
200
500
f/Hz
2000
5000
10k
20k



_20cm_direct (0.00-119.93 s).Spec. Roughness
R'/asper/Bark
0.4
0.35
0.3
0.25
0.2
0.15
0.1
50m
0
Left : 2.91 asper
Right : 2.74 asper
50
100
200
500
f/Hz
2000
5000
10k
20k

Hairdryer 3


_20cm_direct4 (0.00-119.93 s).Spec. Fluctuation Strength
Fls.'/vacil/Bark
1.2m
1m
0.8m
0.6m
0.4m
0.2m
0
Left : 0.00777 vacil
Right : 0.00842 vacil
50
100
200
500
f/Hz
2000
5000
10k
20k


_20cm_direct4 (0.00-119.93 s).Spec. Roughness
R'/asper/Bark
0.4
0.35
0.3
0.25
0.2
0.15
0.1
50m
0
Left : 3.27 asper
Right : 3.42 asper
50
100
200
500
f/Hz
2000
5000
10k
20k

4. Sensory evaluation

This section shows the results obtained during the evaluation of the people response to the sound of the three hairdryers used in the study. At first, explorative interviews were carried out. In these interviews potential users were asked to express in their own words their impressions and opinions about the sound of the products. These interviews, of a qualitative nature, formed the basis for the development of a semantic differential test, in order to assess in a quantitative way these adjectives. Subsequently, a correlation matrix was developed in order to find possible links between the analyzed adjectives.

4.1 The explorative interviews

4 women and 2 men participated in the interviews about the hairdryers, aged between 23 and 29 years (25.7 on average). They are mostly students and use hairdryers with an average frequency of use of 2.6 times per week. People were asked to describe the sound of the hairdryers in their own words. They were also asked to rate the hairdryers and to compare them. (For a sample of this questionnaire see annex 1).

The interviews were conducted in an office of the university. The participants in the project were exposed to the sound of the hairdryers through the recordings which were previously made in the semi-anechoic chamber of the university. Closed headphones model AKG-K81DJ were used for that.

A compilation of the results of the sound evaluation obtained from the interviews for each hairdryer is shown below.

Hairdryer 1

The most frequently mentioned adjectives in the interviews about the sound of this product were soft (mentioned in 4 of the 6 interviews) and not powerful (also found in 4 of 6). The sound of this hairdryer was also described to a lesser extent as weak (in 3 of 6) and not annoying (2 of 6).

The average score obtained for this hairdryer in the interviews was 2,875 (1 the best - 5 the worst). It was chosen as the preferred hairdryer by 2 of the 6 people and the reason for which it was chosen is that it was the most silent.

Hairdryer 2

5 of the 6 interviewed people described the sound of this hairdryer as powerful. Other remarkable adjectives which appeared to a lesser extent were shrill (2 of 6), disturbing (2 of 6) and annoying (2 of 6).

1 of the 6 people chose this hairdryer as a favorite and the reason for their choice was that it gave the sensation of being the most powerful one. The average score for this hairdryer was 3.175 (1 the best - 5 the worst).

Hairdryer 3

People described the sound of this appliance as powerful (mentioned in 3 of the 6 conducted interviews), dirty (in 2 of 6), strong (2 of 6) and disturbing (2 of 6).

It got an average score of 3.175 (1 the best - 5 the worst) and was chosen as the favorite hairdryer by 3 of the 6 interviewees. The reasons for which it was chosen are:

- *"the sound is strong but not as sharp as the HD 2"*
- *"it has a lower sound but powerful"*
- *"its sound is the strongest and it has not this "double sound" effect in the noise."*

4.1.1 Identifications of double subjective pitch and roughness patterns in the sounds

Two important findings about the sounds repeatedly have appeared during the interviews. Both are closely related to the direct recognition of two psychoacoustic parameters.

The following references regarding the perception of a double subjective frequency were found:

- *"there is a sort of double sound"* (HD2)
- *"sounds like two sounds being played at the same time"* (HD1 and HD3)
- *"these hairdryers had another sound added to the noise, like a constant sound in a higher or lower frequency"* (HD1 and HD2)

Regarding the recognition of roughness patterns the following comments were found:

- *“seems like this black and white “ants” that you see sometimes on a TV screen when you are trying to tune a program”* (HD2)

- *“seems like the sound of a broken TV”* (HD3)

- *“sounds like TV snow”* (HD3)

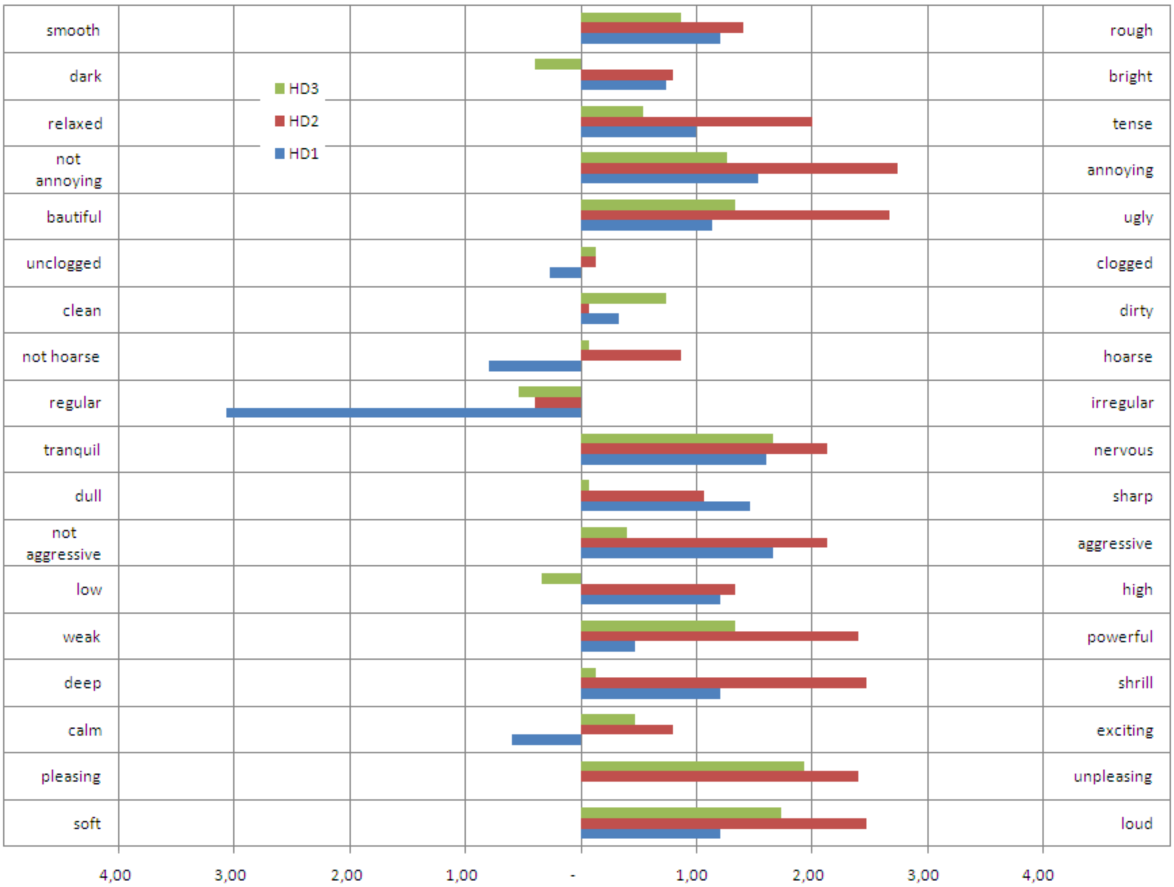
4.2 The semantic differential

10 men and 5 women aged between 20 and 35 years (24.6 years on average), mostly students, participated in the semantic differential test. The test was developed with the adjectives that the interviewees of the previous phase of the project used to describe the sound of the hairdryers.

The test was conducted in an office of the university. The participants were exposed to the recordings of the sound of the hairdryers using closed headphones model AKG-K81DJ. (For a sample of this semantic differential test see annex 2).

The results obtained from the semantic differential test are shown below. The shown values are an average of the responses of the 15 participants in the test and for each one of the hairdryers.

	HD1	HD2	HD3
loud	1,20	2,47	1,73
unpleasing	-	2,40	1,93
exciting	- 0,60	0,80	0,47
shrill	1,20	2,47	0,13
powerful	0,47	2,40	1,33
high	1,20	1,33	- 0,33
aggressive	1,67	2,13	0,40
sharp	1,47	1,07	0,07
nervous	1,60	2,13	1,67
irregular	- 3,07	- 0,40	- 0,53
hoarse	- 0,80	0,87	0,07
dirty	0,33	0,07	0,73
clogged	- 0,27	0,13	0,13
ugly	1,13	2,67	1,33
annoying	1,53	2,73	1,27
tense	1,00	2,00	0,53
bright	0,73	0,80	- 0,40
rough	1,20	1,40	0,87



4.2.1 Correlations between adjectives

From the data obtained from the semantic differential test, a correlation matrix was elaborated in order to find relations between the evaluated adjectives. (The complete correlation matrix is shown in annex 3).

Below, the pairs of adjectives which have a correlation coefficient greater than 0.5 in at least two of the three analyzed hairdryers are given. Both, the positive and negative correlations were taken into account in order to be chosen.

		HD1	HD2	HD3
loud	unpleasing	-0,03	0,87	0,65
loud	rough	0,51	0,20	0,54
unpleasing	annoying	0,51	0,39	0,58
shrill	high	0,65	0,59	0,49
shrill	sharp	0,26	0,57	0,51
high	sharp	0,07	0,63	0,77
high	bright	0,56	0,44	0,56
agressive	nervous	0,56	0,54	0,55
agressive	annoying	0,57	0,80	0,60
nervous	ugly	0,64	0,22	0,62
nervous	annoying	0,46	0,50	0,88
nervous	tense	0,80	0,58	0,74
nervous	rough	0,65	0,13	0,63
irregular	rough	0,35	0,55	0,73
dirty	rough	0,10	0,63	0,64
ugly	annoying	0,62	0,73	0,68
ugly	tense	0,91	0,31	0,56
ugly	rough	0,38	0,66	0,81
annoying	tense	0,58	0,64	0,79
hoarse	bright	-0,77	-0,34	-0,58

5. Conclusions

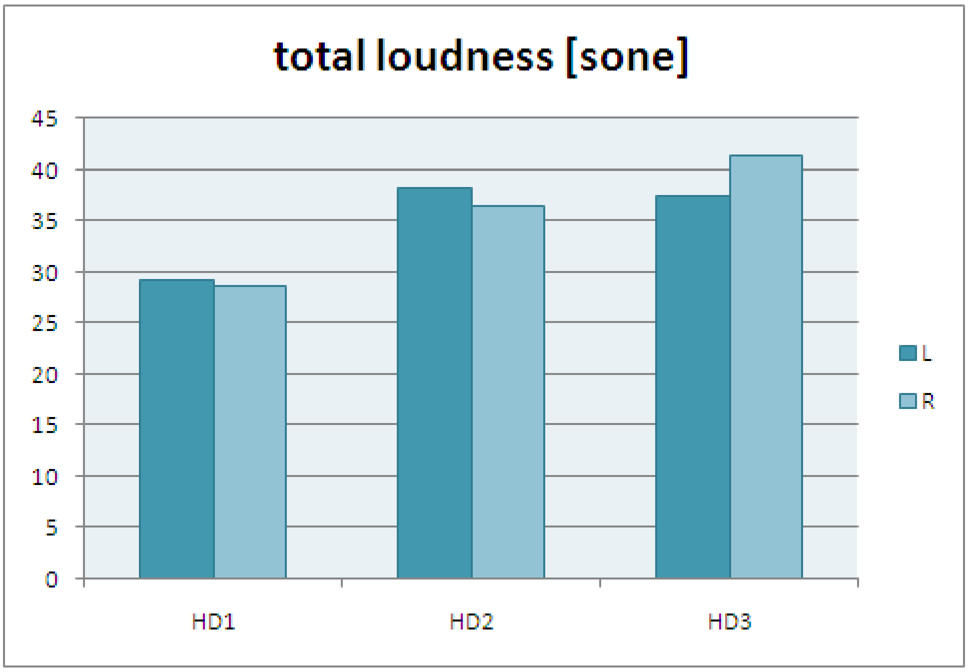
5.1 Reinforcement of frequencies

When a small electric motor rotating at high speeds is put inside a cylinder it can be expected that certain frequencies will be heavily reinforced due to the standing waves that this originates inside this cylinder. That is why the strengthening of certain frequencies is a common feature in the sound of a hair dryer. The characteristics of these peaks and their position in the spectrum will largely determine how the sound of the hair dryer will be perceived by users.

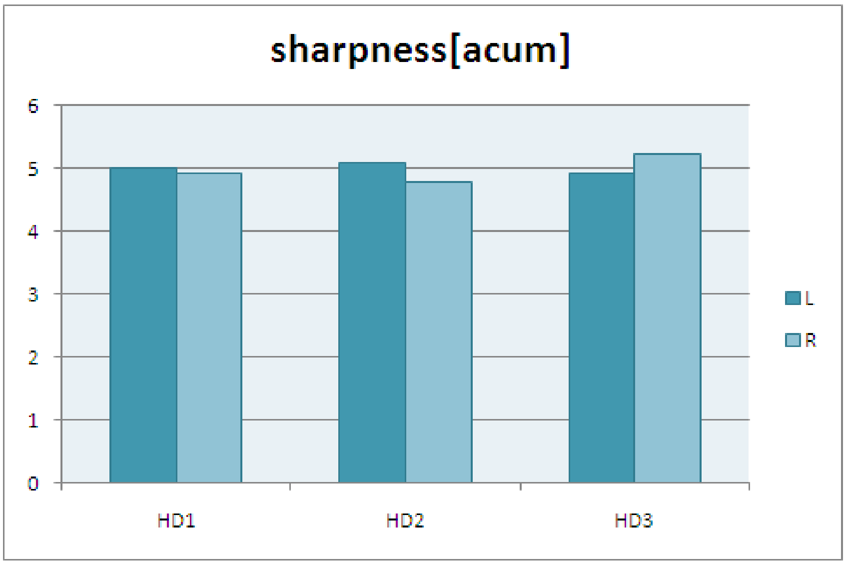
These frequencies capture the listener's attention and are able to mask other patterns that appear in the sound.

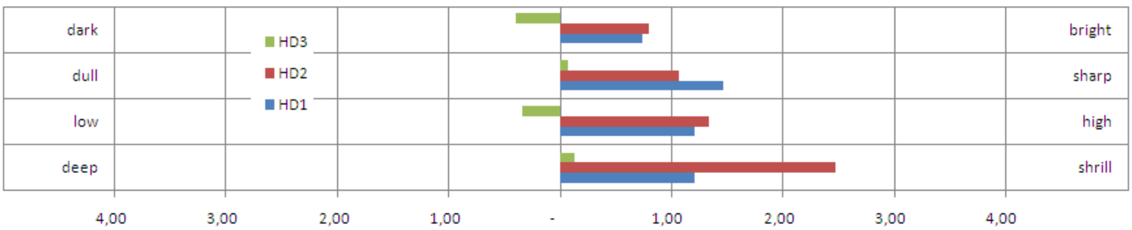
A clear example of the effects produced by the reinforcement of certain frequencies clearly appears in the hairdryer 2. A peak appears at the frequency of 1683 Hz with 70.14 dBA:

First, observe the effects on the perception of loudness. The results of the psychoacoustic analysis and sensory evaluation of loudness for the three hairdryers are presented below.



As revealed by the results of the semantic differential test, the hairdryer 2 has been clearly considered much louder than what was expected by the mathematical model used for the calculation of loudness. The primarily responsible of this strong loudness sensation for the hairdryer 2 appears to be the mentioned peak, which gives rise to the louder critical band within the spectrum of the three hairdryers. This peak captures the listener's attention to a large extent and also determines the subjective pitch that is perceived while listening to the sound of the hairdryer. Furthermore, this subjective pitch is also the highest within the three hairdryers. That is why the sharpness sensation of this hairdryer is higher compared to what was estimated by the mathematical model used during the psychoacoustic analysis of sound:





By increasing the loudness and sharpness sensation this peak is also attributed to increase the power sensation and also unwanted sensations such as annoyance, tension, aggressiveness and unpleasantness for example.

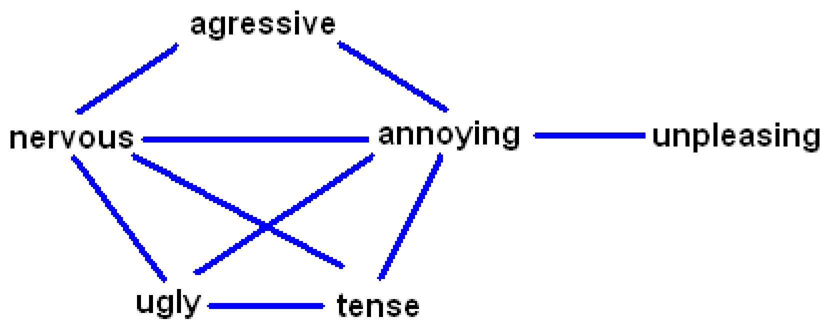
These peaks inside the spectrum characterize much the sound of the product, which is why their effects should be evaluated thoroughly. Its effects will be mainly dependent on the frequency at which these peaks appear. One way to directly evaluate the effects of these peaks would be by comparing the results of the product sound evaluation with and without the peak. The peak would be eliminated from the spectrum by a band-stop filter. Another possibility to determine the effects of these peaks would be artificially strengthening a frequency within the spectrum of the sound of a hairdryer through the filtering of the signal. To further carry out a new evaluation and observe the changes it has caused in the perception of the sound with respect to the unfiltered signal.

It should also be noted that, as shown in the sensory evaluation section, people identified dual subjective pitch patterns in the sound of the hairdryers. This sensation is caused by the occurrence of more than one of these reinforced frequencies within the spectrum. These patterns were considered as annoying in all cases that were mentioned by interviewees.

5.2 Power and aggressiveness

From the results obtained in the interviews it is known that there are two main aspects that people consider about the sound of a hairdryer when they have to choose one product or another: On the one hand, the power sensation that the sound has and on the other hand, the absence of annoying patterns in the sound. Increasing the power sensation and reducing annoyance is therefore essential in order to achieve a good sound for a hairdryer. Therefore it is important to identify what features within the sound of a hairdryer causes this effect.

As it has been reflected in the study, a good way to evaluate the balance between power and annoyance is by assessing the aggressiveness sensation that causes the sound in comparison with its power sensation. Aggressiveness can be regarded as an excess of power or as a negative connotation of power. Furthermore, aggressiveness appears to be a good indicator of many unwanted sensations in the target sound. The relationships between aggressiveness and these unwanted impressions are shown below. The blue lines connect the adjectives that are correlated with a correlation coefficient greater than 0.5 in at least two of the three hairdryers that were evaluated in the semantic differential test.



As can be seen, the hairdryer 3 has the highest power / aggressiveness ratio in comparison to the other two models. Also this hairdryer has been chosen as a favorite by 50% of the participants in the interviews.

Then, the significant differences found between this appliance and the other two will be analyzed in order to clarify which features within the spectrum of this hairdryer provide it with that better power / aggression ratio.

There are two basic differences in the spectrum of this hairdryer compared to the other two models: Firstly, its high content of roughness patterns; Secondly, it is the hairdryer with the greatest loudness for the critical bands between 8 and 14 Barks, and also it has the lower subjective pitch.

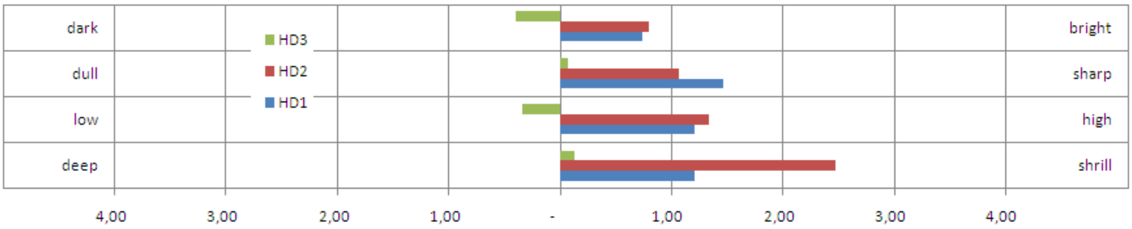
5.2.1 Roughness patterns and power

Regarding the manner in which psychoacoustic parameters interfere in the generation of power sensation, it is known that it directly increases with loudness and sharpness. Nevertheless, when we talk about how roughness patterns interfere in the power sensation the evaluation becomes more complicated. Certain roughness patterns can produce power sensation, but others may be simply annoying [8]. It would be needed another study with major depth in order to determine in which way different roughness patterns can provide power sensation to the sound of a hairdryer.

However, most of the negative aspects found in the sound of the hairdryer 3 are directly due to its high roughness. Therefore, a priori this does not seem to be the most plausible cause of its better power / aggressiveness ratio.

5.2.2 Low-frequency and power

The other feature that is also notable on this hairdryer is that its sound has been considered the dullest, as shown below in the results obtained from the semantic differential test for adjectives related to high-frequency presence.



This greater presence of low-frequency seems to make the difference between the sound of this hairdryer and the other two models providing its sound with a greater power sensation but without causing discomfort.

This idea is supported by the arguments that people gave for choosing the sound of this hair dryer as their favorite during the interviews:

- *"the sound is strong but not as sharp as the HD 2"*

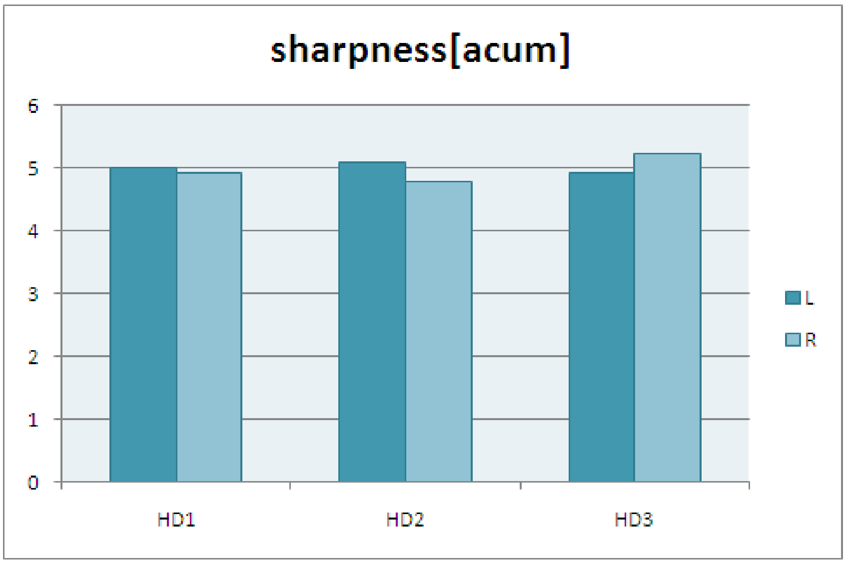
- *"it has a lower sound but powerful"*

Therefore, we find ourselves facing a very desirable feature in the sound of a hairdryer.

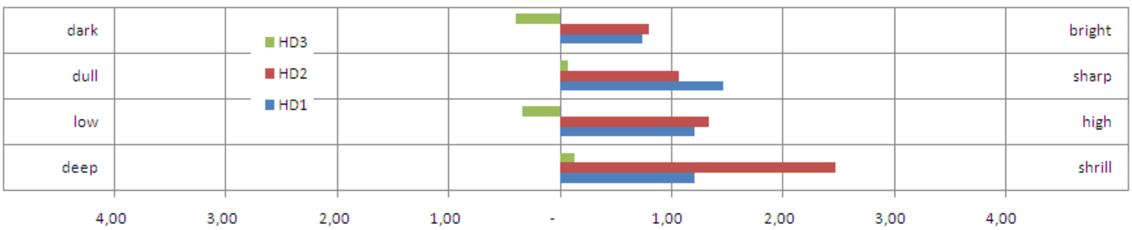
5.3 Considerations about sharpness model

During the course of this study it has been observed that the sharpness model used for the analysis of the psychoacoustic parameters of the sound has not coincided with the sharpness sensation that people had.

First, obverse the results obtained from the sharpness analysis through Aures' model for each one of the hairdryers:

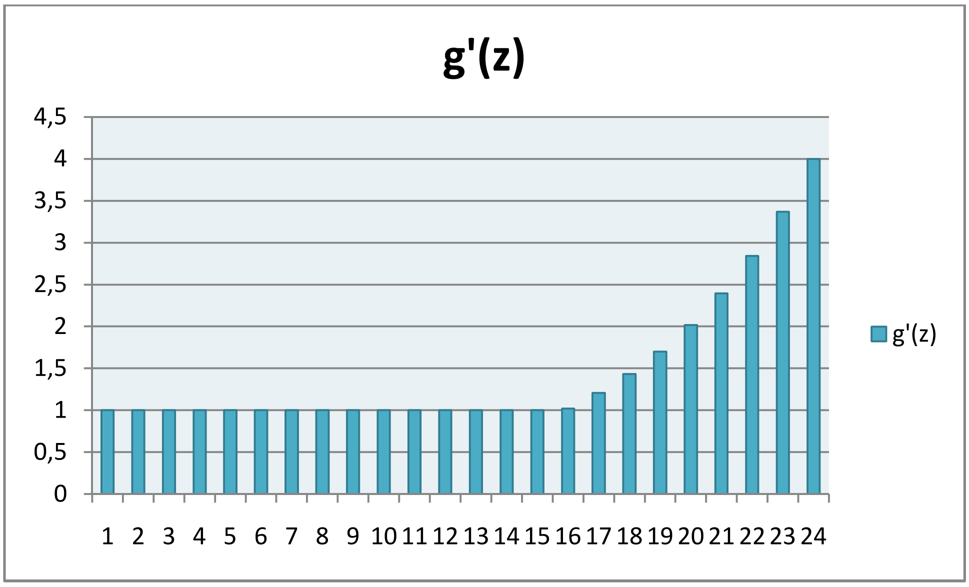


Below, observe the results from the sensory evaluation for four adjectives which are directly related to the presence of high-frequency in the sound:



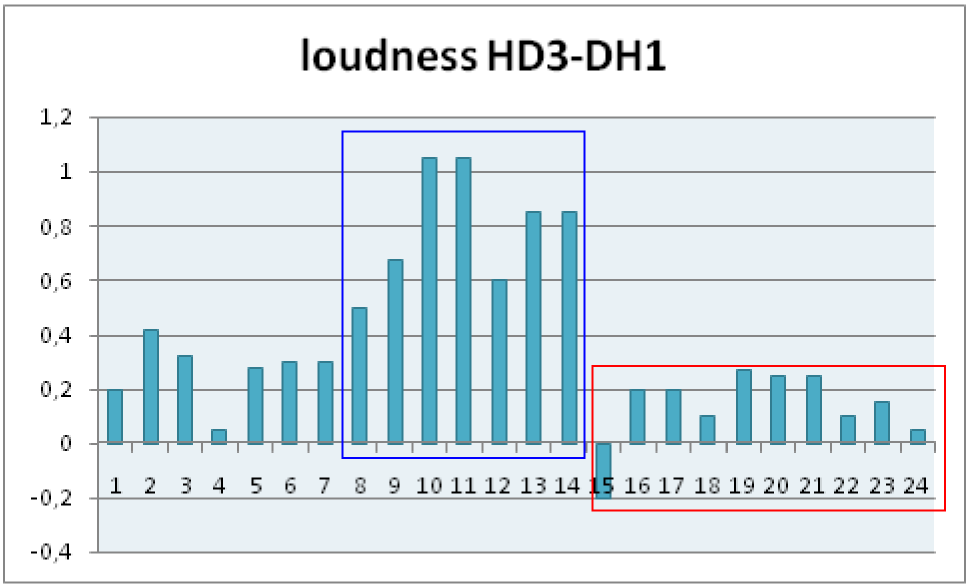
The hairdryer 3 has been considered as dull, even though it has the greatest high-frequency content in its spectrum compared to the other two appliances. As can be seen, this perception is not due to a lesser content of high-frequency on the spectrum, but to a greater low-frequency content compared to the other two. That is why the mathematical model used is not able to give us a real approximation of how the sound will be perceived by people as the presence of low-frequency in the spectrum does not contribute in any way to sharpness calculation.

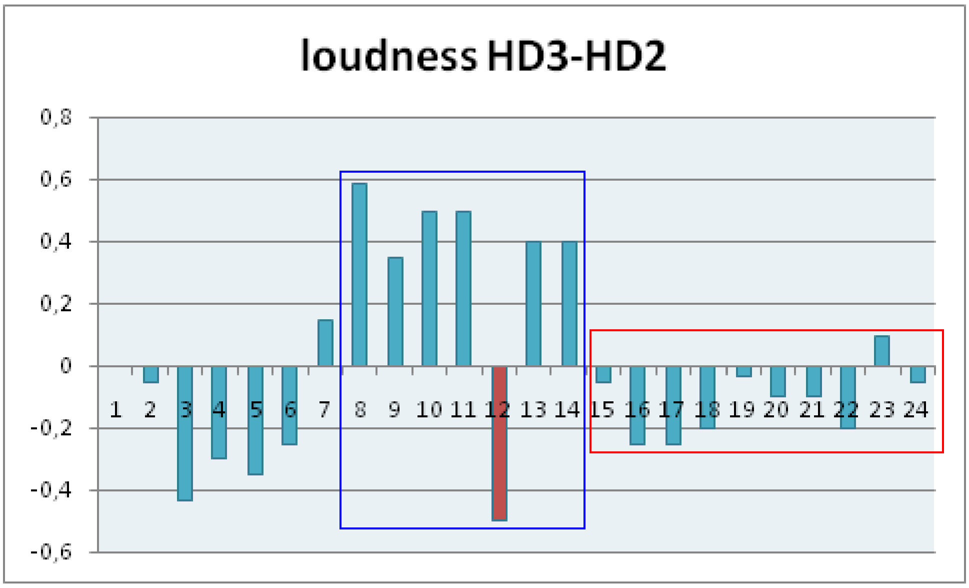
As it is explained in the section about the psychoacoustic analysis of the sound, Aures' model takes the loudness level for each critical band and assigns a weight to them, in order to carry out sharpness calculation. This weight increases together with frequency from 16 Barks. It is represented by the weighting function g '(z):



In the case of the hairdryers used in the study, all of them share a very similar spectrum at high frequencies, which is why the model almost does not find sharpness differences between them.

Where a big difference of loudness can be found, is between 8 and 14 critical bands. The differences of the loudness level for each critical band between the hairdryer 3 and the other two appliances.

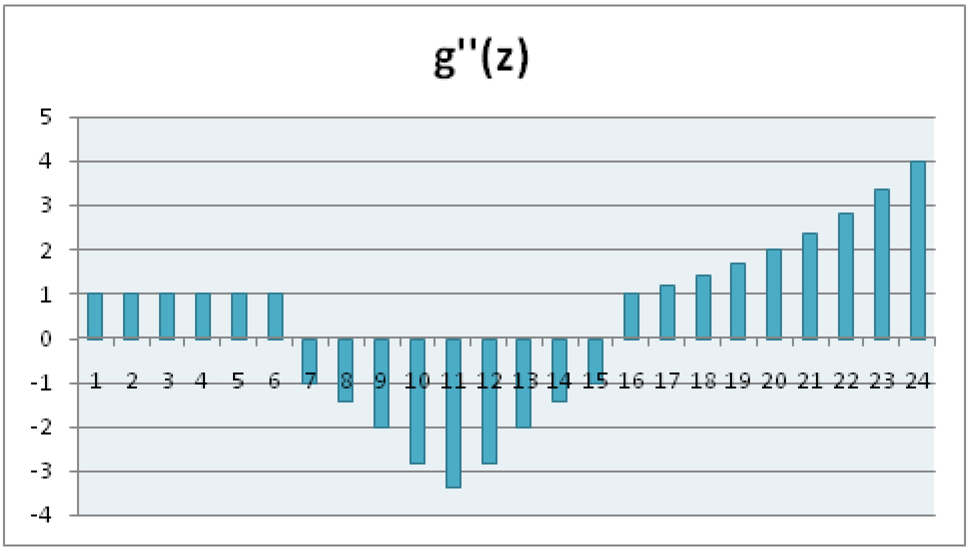




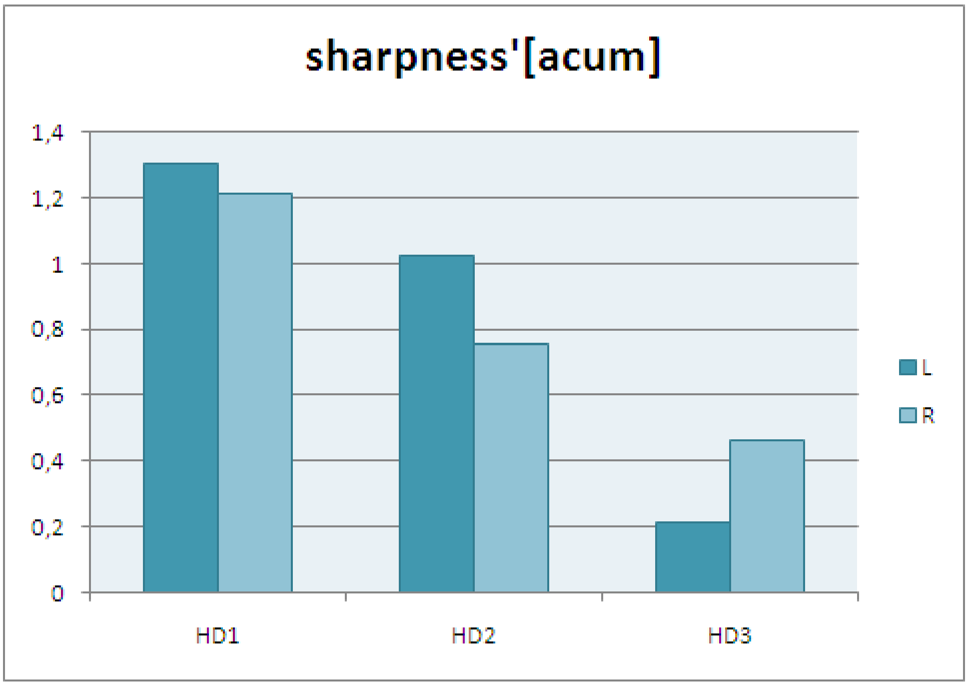
As it can be seen, loudness levels above 16 Barks differ very little between the hairdryers, but around 11 Barks appears an area in which the differences between loudness levels are very significant. These bands, which make the difference between the hairdryer 3 and the other two, are practically not taken into account for the calculation of sharpness. In order to obtain a more realistic result from the calculation of sharpness, the loudness levels of these critical bands should contribute in a negative way.

This leads to consider the possibility of a model that takes into account the negative contributions of these critical bands. This can be accomplished by simply changing the weighting function. One might note that this would not be a sharpness model but rather a dullness-sharpness model, because having these negative contributions in the formula it is possible to obtain negative results. The negative values of sharpness would be considered as positive values of dullness and vice versa.

As an example of the above mentioned, the following weighting function is shown, where negative weights for the critical bands from 8 to 14 Barks have been added.



The sharpness values obtained by using this weighting function for the three hairdryers are shown below:



A further study should be conducted to check the feasibility of a specific weighting function for such sounds, since the scope of this study does not go beyond the fact of just raising this idea.

The method of obtaining the weighting function would be the same that has been followed here:

- Observe the differences of loudness per critical band between all the studied appliances.

- Carry out a sensory evaluation of sharpness.

- Try to assign weights to the critical bands trying to adjust at maximum the results of sharpness calculation with the results obtained through the sensory evaluation.

5.4 Roughness evaluation

During the development of this study it has been placed in evidence the unfeasibility of using the adjective ‘rough’ in order to assess roughness sensation. The concept of rough sound is pretty abstract for people and its definition may seem ambiguous when there is no certain knowledge of psychoacoustics. That is why the concept that the person has about rough sound may differ regarding the meaning attached to it from the point of view of psychoacoustics or from the concept that other person can have about roughness.

However, people have been able to identify roughness patterns in the sound of the hairdryers during the explorative interviews, as shown in the section about sensory evaluation. Each person has defined these patterns in his own words but trying to describe the same sensation:

- *“seems like this black and white “ants” that you see sometimes on a TV screen when you are trying to tune a program”* (HD2)

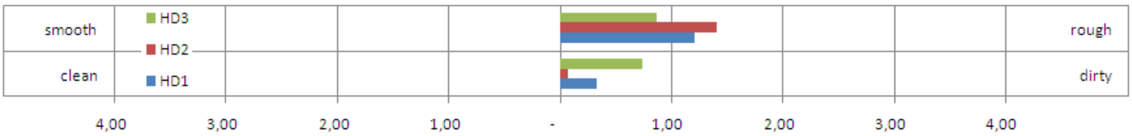
- *“seems like the sound of a broken TV”* (HD3)

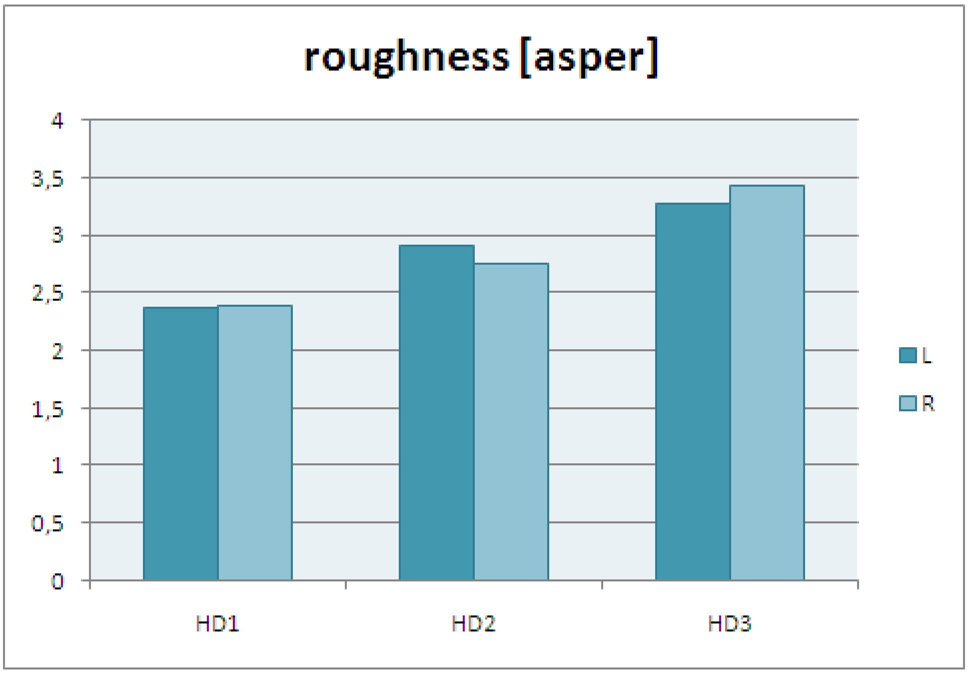
- *“sounds like TV snow”* (HD3)

Moreover, the adjective ‘rough’ was not mentioned on any occasion during the interviews while describing the sound of the hairdryers, but the adjective ‘dirty’ was. This adjective was mentioned in 2 of the 6 interviews, and both times it was used to describe the sound of the hairdryer 3. Furthermore, 2 of the 3 comments that show a clear identification of roughness patterns in their sound were about the hairdryer 3: "broken TV" and "TV snow".

On this basis it was decided to perform the quantification of roughness sensation through the use of the adjective ‘dirty’ instead of the adjective ‘rough’.

As shown below, the results of the evaluation of this adjective show the hairdryer 3 as the most rough, in accordance with the results obtained from the analysis of the psychoacoustic parameters of the sound:





Therefore, the adjective 'dirty' seems to be more intuitive for people in order to assess roughness patterns, according with the results of the interviews.

It is interesting to highlight the importance of the explorative interviews in order to carry out a product sound evaluation. Without these interviews it would have been impossible to perform a meaningful assessment of roughness sensation.

5.5 Summary

- The effects of the reinforced frequencies should be studied exhaustively and in depth. These peaks in the spectrum strongly characterize the sound of the product, they are able to mask other patterns and determine the subjective pitch of the sound.
- The occurrence of more than one reinforced frequencies in the spectrum can generate a dual subjective pitch sensation. These patterns were considered as annoying in all cases that were mentioned by interviewees.
- Two main aspects of the sound of a hairdryer are considered by people when they have to choose one product or another: the power sensation and the annoying patterns. Therefore, to get a good sound for such products, it is necessary to maximize the power sensation and minimize the annoying patterns in the sound.
- A good way to evaluate the sound quality of a hairdryer would be to observe the ratio between power and aggressiveness sensation that it transmits. Higher power / aggressiveness ratio means more quality.
- The presence of low frequency content increases the power sensation without adding annoying patterns to the sound.
- It may be feasible to adapt the weighting function of Aures, according to experimental data, in order to obtain a model that would be able to predict sharpness sensation for such sounds, without the need of a reference sound from which assign sharpness values, as Bismark model does. This new model may be feasible also for the sound of vacuum cleaners.
- The use of the adjective ‘dirty’ has offered better results than the adjective ‘rough’ in order to quantify roughness sensation during the sensory evaluation.
- The explorative interviews have proved to be crucial in order to carry out the product sound evaluation. Thanks to these interviews, it has been possible to perform a consistent roughness evaluation. They also allowed knowing the effects of dual subjective pitch patterns in the sound.

6. Annexes

6.1 Annex I

Product Sound Evaluation

Bachelor's Thesis – M. Espinosa

Hair dryer 1

Rate this hair dryer (1 the best – 5 the worst)

1 2 3 4 5

Give your thoughts about this hair dryer.

Hair dryer 2

Rate this hair dryer (1 the best – 5 the worst)

1 2 3 4 5

Give your thoughts about this hair dryer.

Hair dryer 3

Rate this hair dryer (1 the best – 5 the worst)

1 2 3 4 5

Give your thoughts about this hair dryer.

Which one of this three hair dryers would you prefer?

____

Why?

____
____
____
____
____
____
____
____
____

Date:

Age:

Gender:

How often do you use a hair dryer during the week?

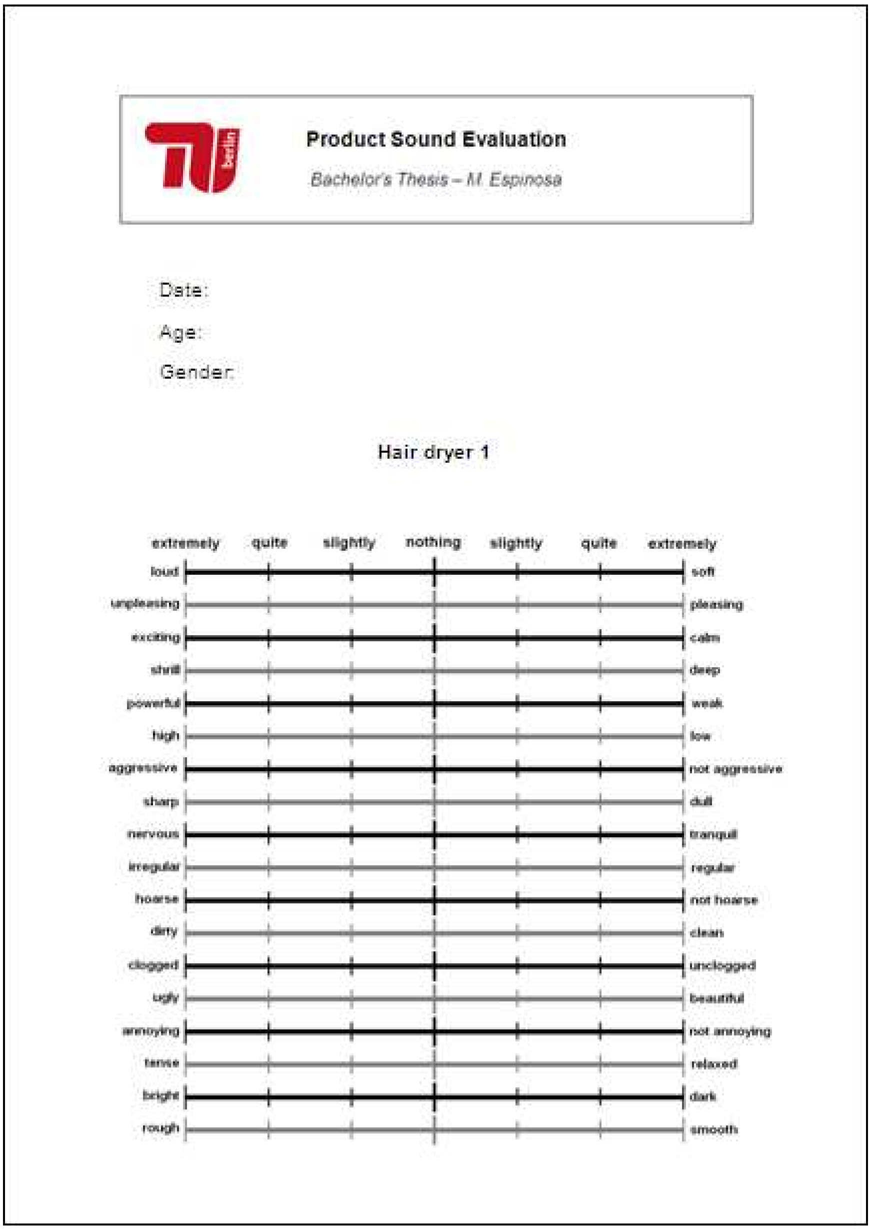
Do you remember which was the reason for the choice of your current hair dryer?

Do you feel disturb by the hair dryer sound if someone else in the family is using this hair dryer?

May I ask you how often you visit a medical doctor to address hearing problems?

Thank you very much for your collaboration!

6.2 Annex II



Product Sound Evaluation

Bachelor's Thesis – M. Espinosa

Date:

Age:

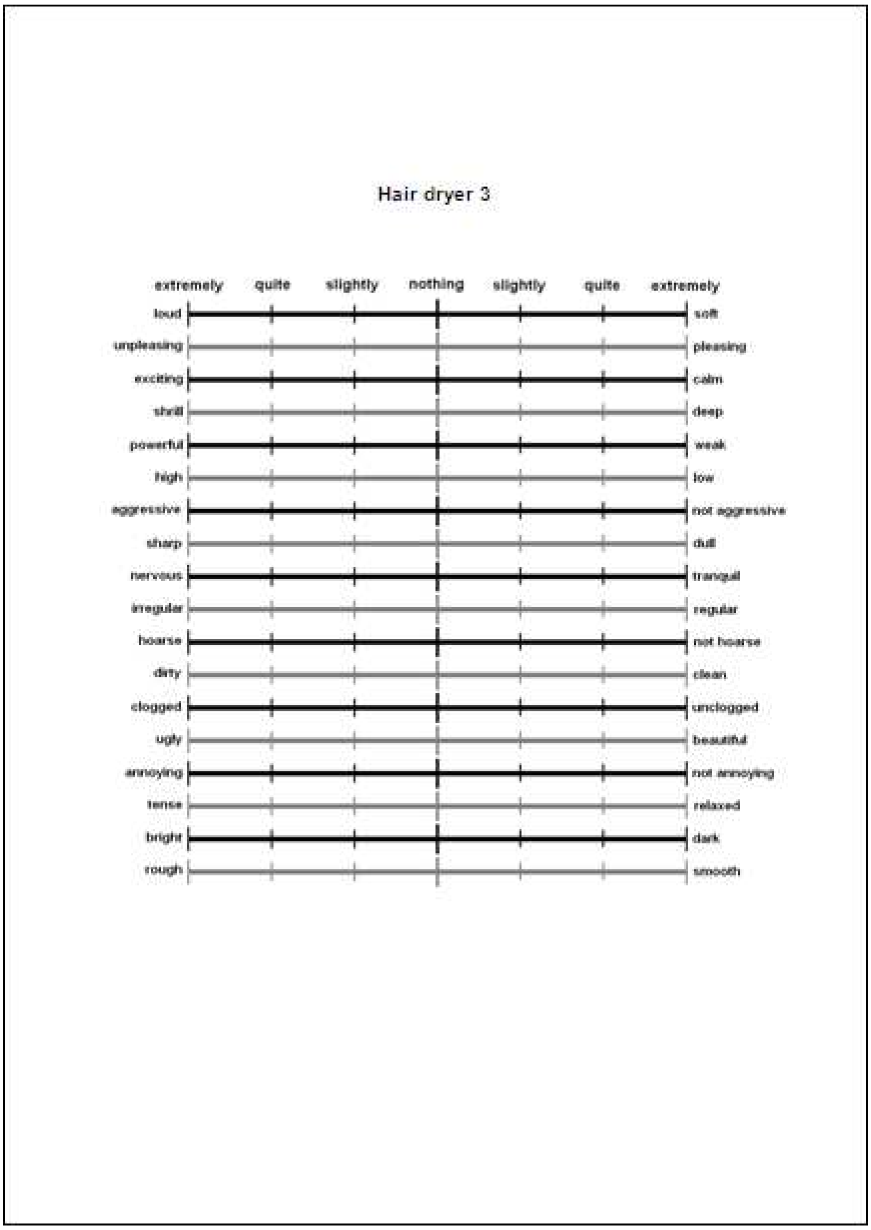
Gender:

Hair dryer 1

	extremely	quite	slightly	nothing	slightly	quite	extremely	
loud								soft
unpleasing								pleasing
exciting								calm
shrill								deep
powerful								weak
high								low
aggressive								not aggressive
sharp								dull
nervous								tranquil
irregular								regular
hoarse								not hoarse
dirty								clean
clogged								unclogged
ugly								beautiful
annoying								not annoying
tense								relaxed
bright								dark
rough								smooth

Hair dryer 2

	extremely	quite	slightly	nothing	slightly	quite	extremely	
loud								soft
unpleasing								pleasing
exciting								calm
shrill								deep
powerful								weak
high								low
aggressive								not aggressive
sharp								dull
nervous								tranquil
irregular								regular
hoarse								not hoarse
dirty								clean
clogged								unclogged
ugly								beautiful
annoying								not annoying
tense								relaxed
bright								dark
rough								smooth


Hair dryer 3
extremely
quite
slightly
nothing
slightly
quite
extremely
loud
soft
unpleasing
pleasing
exciting
calm
shrill
deep
powerful
weak
high
low
aggressive
not aggressive
sharp
dull
nervous
tranquil
irregular
regular
hoarse
not hoarse
dirty
clean
clogged
unclogged
ugly
beautiful
annoying
not annoying
tense
relaxed
bright
dark
rough
smooth

6.3 Annex III

	loud			unpleasing		
unpleasing	-0,03	0,87	0,65			
exciting	-0,41	-0,17	0,11	0,53	0,00	0,16
shrill	0,03	0,49	0,20	-0,13	0,42	0,13
powerful	0,30	0,53	0,22	0,01	0,48	0,09
high	0,25	0,44	0,23	-0,13	0,32	0,24
aggressive	0,32	0,33	0,37	0,58	0,49	0,32
sharp	0,24	0,19	0,13	0,31	0,12	0,11
nervous	0,41	0,33	0,31	0,09	0,27	0,57
irregular	-0,07	-0,08	0,32	-0,22	-0,10	0,02
hoarse	-0,03	0,23	0,11	0,43	0,54	0,00
dirty	0,30	0,20	0,61	-0,22	0,24	0,07
clogged	0,27	0,06	-0,10	0,07	0,29	0,33
ugly	0,17	0,35	0,61	0,22	0,57	0,48
annoying	0,03	0,21	0,38	0,51	0,39	0,58
tense	0,25	0,15	0,36	0,09	0,21	0,44
bright	0,08	-0,10	0,04	-0,28	-0,15	0,01
rough	0,51	0,20	0,54	-0,31	0,35	0,23
	exciting			**shrill**		
shrill	0,14	-0,34	0,10			
powerful	0,24	-0,08	0,13	0,12	0,64	0,41
high	-0,23	-0,43	0,00	0,65	0,59	0,49
aggressive	0,24	-0,08	0,43	0,08	0,40	0,38
sharp	0,33	-0,46	-0,12	0,26	0,57	0,51
nervous	-0,24	0,13	0,52	0,36	0,18	0,14
irregular	0,03	0,32	0,35	-0,49	-0,08	0,19
hoarse	0,11	0,14	0,08	-0,14	-0,08	-0,09
dirty	0,04	-0,12	0,17	0,16	0,14	0,34
clogged	-0,02	-0,01	0,61	0,30	-0,23	-0,26
ugly	-0,07	-0,08	0,30	0,30	0,24	0,29
annoying	0,06	-0,09	0,36	0,39	0,24	0,12
tense	-0,12	-0,05	0,71	0,32	0,10	0,22
bright	0,05	-0,44	0,02	0,16	0,07	0,47
rough	-0,55	-0,19	0,55	0,07	0,26	0,20

	powerful			high		
high	-0,24	0,41	0,12			
aggressive	0,06	0,51	0,30	0,04	0,58	0,45
sharp	0,05	0,26	0,07	0,07	0,63	0,77
nervous	-0,29	0,58	0,22	0,38	0,03	0,26
irregular	-0,25	0,03	0,10	-0,33	0,06	0,46
hoarse	0,07	0,26	-0,04	-0,33	-0,23	-0,44
dirty	-0,02	-0,07	0,19	0,36	0,22	0,33
clogged	-0,20	0,10	-0,29	0,33	-0,21	-0,17
ugly	-0,20	0,13	0,06	0,47	0,10	0,18
annoying	-0,26	0,26	0,18	0,41	0,22	0,43
tense	-0,32	0,25	0,27	0,46	0,00	0,42
bright	-0,06	-0,09	0,24	0,56	0,44	0,56
rough	0,02	0,12	0,08	0,17	0,04	0,37

	aggressive			sharp		
sharp	0,35	0,57	0,37			
nervous	0,56	0,54	0,55	0,38	0,08	0,32
irregular	-0,16	0,07	0,50	-0,07	-0,21	0,62
hoarse	0,46	0,23	0,03	0,32	-0,39	-0,56
dirty	-0,28	0,13	0,32	0,39	0,09	0,57
clogged	0,73	0,13	0,15	0,23	-0,25	-0,28
ugly	0,31	0,49	0,71	-0,09	-0,02	0,37
annoying	0,57	0,80	0,60	0,09	0,36	0,43
tense	0,42	0,41	0,69	-0,04	0,00	0,34
bright	-0,25	0,11	0,26	-0,28	0,18	0,41
rough	0,04	0,22	0,77	0,15	-0,03	0,37

	nervous			irregular		
irregular	0,07	0,09	0,46			
hoarse	0,23	0,29	0,08	0,07	0,04	-0,36
dirty	-0,08	-0,13	0,20	0,18	0,48	0,67
clogged	0,59	0,21	0,40	-0,05	0,11	-0,12
ugly	0,64	0,22	0,62	0,00	0,18	0,44
annoying	0,46	0,50	0,88	-0,50	0,07	0,38
tense	0,80	0,58	0,74	0,16	-0,07	0,57
bright	-0,16	-0,32	-0,11	0,07	-0,33	0,32
rough	0,65	0,13	0,63	0,35	0,55	0,73

	hoarse			dirty		
dirty	-0,04	0,29	-0,20			
clogged	0,26	0,79	0,37	-0,05	0,54	-0,23
ugly	-0,09	0,52	0,23	-0,13	0,49	0,61
annoying	0,07	0,24	0,11	-0,35	0,14	0,29
tense	-0,05	0,27	-0,05	-0,15	-0,10	0,37
bright	-0,77	-0,34	-0,58	0,32	-0,36	0,22
rough	0,14	0,49	0,15	0,10	0,63	0,64
	clogged			**ugly**		
ugly	0,25	0,44	0,23			
annoying	0,54	0,18	0,40	0,62	0,73	0,68
tense	0,52	0,16	0,43	0,91	0,31	0,56
bright	-0,07	-0,48	-0,32	0,26	-0,11	-0,06
rough	0,14	0,50	0,21	0,38	0,66	0,81
	annoying			**tense**		
tense	0,58	0,64	0,79			
bright	-0,04	0,12	-0,21	0,21	0,23	-0,01
rough	-0,11	0,39	0,65	0,47	0,21	0,74
	bright					
rough	-0,19	-0,32	0,05			

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