METHODICAL MEASUREMENT OF ACOUSTICAL IMPEDANCE AND REPLACEMENT SENSIBILITY.

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ABSTRACT

The acoustical impedance is measured using an impedance tube specially designed for these requirements. The differences among loads caused by headphones and free ear situation, as well as the variation among the impedances from various headphones are studied. Another parameter to consider is the sensibility of this impedance to the replacement of the headphone. These results are used in other investigation relating the impedance of these headphones to different psychoacoustic effects, such as “in head localization” or the missing of 6 dB with headphones reproduction.

RESUMEN

En este artículo se muestran las medidas de la impedancia acústica que presentan diversos auriculares. Éstas han sido realizadas usando un tubo de impedancias especialmente diseñado al efecto. Se observan variaciones entre distintos auriculares así como con respecto a la audición en espacio libre. Otro parámetro considerado es la sensibilidad de la medida a la recolocación de los auriculares. Los resultados han sido usados en investigaciones posteriores que relacionan las variaciones mencionadas con diferentes efectos psicoacústicos como la localización del sonido en el interior de la cabeza del oyente o la pérdida de 6 dB con la reproducción con auriculares.

1. INTRODUCTION

When sound reproduction is been performing with headphones, some psychoacoustics phenomenas appear. “In-head localisation” and the “missing of 6 dB” are some of them ([1]-[2]). A possible reason for this kind of problems could be the closing of the ear. With this hypothesis, it can be interesting to get the impedance from different headphones in order to compare later on the measurements with those effects and watch whether some correlation arises.

The impedance from 25 different headphones is measured. A tube specially designed for this purpose is used. This impedance tube is built following [4]. After these measurements are obtained, they are compared with the impedance of the free ear.

The physical basis of impedance acquisition, as well as the procedure used together with the headphones analysed, is described in section 2. Section 3 shows the impedance measurements and the replacement sensibility of these. Finally, section 4 outlines the conclusions reached with this work.

2. MEASUREMENT DESCRIPTION

2.1 Physical Basis

The measurement scheme consists in the impedance tube with a loudspeaker placed at the end. The loudspeaker generates a stationary wave. The sample to be measured, the headphone in this case, is located in the other tube input. The pressure in two different points placed along the tube is obtained. With these two measurements, it is possible to obtain the complex amplitudes of the emitted and reflected waves. With this information, the headphone reflection can be easily calculated and, consequently, the impedance. Figure 1 shows this description.

The clasical characteristic equations of a plane wave for the sound pressure $\underline{p}$(x,t) and the vibration velocity $\underline{v}$(x,t) along the 'x' axis are presented in (1.1) and (1.2).

$$\underline{p}(x,t) = \left(\underline{p}_t \cdot e^{-jkx} + \underline{p}_r \cdot e^{jkx}\right) \cdot e^{j v t} \qquad (1.1)$$

$$\hat{\underline{v}}(x,t) = \left[\left(\underline{v}_t \cdot e^{-jkx} - \underline{v}_r \cdot e^{jkx}\right) \cdot e^{j v t}\right]\hat{x} \qquad (1.2)$$

It is a well-known process to get the reflection coefficient from (1.1) and (1.2). This is shown in (1.3), where Z_L is the characteristic impedance, a scalar value that only depends on the medium, free space in our case. Therefore, it is a fixed value. $\underline{Z}_A$ is the impedance at the end of the tube (*x=0*). It will be the headphone impedance in our future measurements. The relationship between $\underline{Z}_A$ and Z_L is also expressed with the $\underline{m}$ factor, (1.4).

$$\underline{R} = \frac{\underline{p}_r}{\underline{p}_t} = \frac{\underline{p}_0 - Z_L \cdot \underline{v}_0}{\underline{p}_0 + Z_L \cdot \underline{v}_0} = \frac{\underline{Z}_A - Z_L}{\underline{Z}_A + Z_L} \qquad (1.3)$$

$$\underline{m} = \frac{\underline{Z}_A}{Z_L} = \frac{1 + \underline{R}}{1 - \underline{R}} \qquad (1.4)$$

Now it is necessary to obtain $\underline{R}$ starting from the complex pressure measured in two different points along the tube. The first measurement point will be situated at a distance '***l***' from the end of the tube. The second point will be separated '**s**' from this first point , as shown in Figure 1.

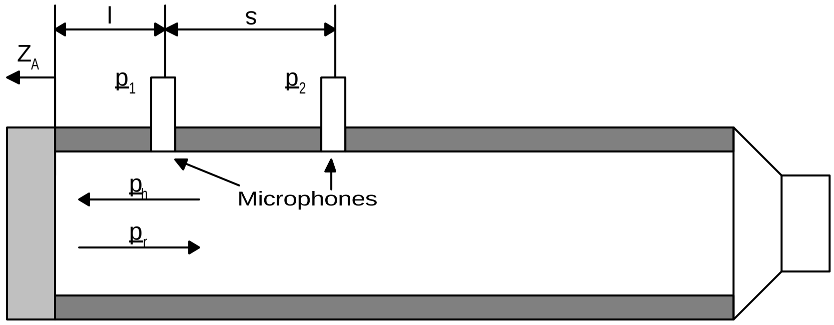

Figure 1: Diagram of the impedance tube.

Using equation (1.1), the pressure in points 1 and 2 ($\underline{p}_1$ and $\underline{p}_2$ respectively) can be expressed as showing in (1.5) and (1.6).

$$\underline{p}_1 = \underline{p}_t \cdot e^{jkl} + \underline{p}_r \cdot e^{-jkl} \qquad (1.5)$$

$$\underline{p}_2 = \underline{p}_t \cdot e^{jkl} \cdot e^{jks} + \underline{p}_r \cdot e^{-jkl} \cdot e^{-jks} \qquad (1.6)$$

Now, solving expressions (1.5) and (1.6) for $\underline{P}_t$ and $\underline{P}_r$, (1.7) and (1.8) are calculated.

$$\underline{p}_t = e^{-jkl} \frac{\underline{p}_2 - \underline{p}_1 \cdot e^{-jks}}{e^{jks} - e^{-jks}} \qquad (1.7)$$

$$\underline{p}_r = e^{-jkl} \frac{\underline{p}_1 \cdot e^{jks} - \underline{p}_1}{e^{jks} - e^{-jks}} \qquad (1.8)$$

Substituting expressions (1.7) and (1.8) in (1.3), the reflection factor can be expressed as,

$$\underline{R} = \frac{\underline{p}_r}{\underline{p}_t} = e^{j2kl} \frac{\underline{p}_1 \cdot e^{jks} - \underline{p}_2}{\underline{p}_2 - \underline{p}_1 \cdot e^{jks}} \qquad (1.9)$$

It has been shown that it is possible to get the impedance at the end of the tube starting from the reflection value. Therefore, the impedance at the end of the tube can be calculated from the pressure of points 1 and 2.

Using this method, critical frequencies appear when the wavelength, λ, is multiple of half of the distance between the two points used in the measurements, *s/2*. When the distance between the two microphones can be expressed as $n \times l/2$ with $n \in \{1,2,3,\ldots\}$, it is not possible to calculate the impedance, since the pressure measured in these two points is the same. To solve this, a new third measurement, $\underline{P}_3$, is included.

Using measurements from points 1 and 2 and from points 1 and 3, two different calculations of the reflection are obtained, $\underline{R}_1$ and $\underline{R}_2$. Distance between point 1 and 3 should not be a multiple of the distance between point 1 and 2, *'s'* in Figure 1. This way, the critical frequencies for the two calculations will not be the same. From these two reflection coefficient and equation (1.3), it is easy to obtain the respective impedance measurements, $\underline{Z}_{A1}$ and $\underline{Z}_{A2}$. The final impedance is obtained from the equation (1.10).

$$\underline{Z}_A = \frac{\sin^2(ks_1) \cdot \underline{Z}_{A1} + \sin^2(ks_2) \cdot \underline{Z}_{A2}}{\sin^2(ks_1) + \sin^2(ks_2)} \qquad (1.10)$$

The calculation of the three pressure points are not carried out at the same time, since only one microphone is used. Instead of that, they are done consecutively with the same microphone. All the conditions during the three measurements must remain. If not, the obtained impedance would not be right. So, the position of the headphone must be the same.

2.2 Description Of The Measurement Procedure

An artificial pinna made of plastic is placed at the tube ending. Moreover, different headphones are placed at that point as well. With the approach presented in previous section, the impedance presented from inside the ear outwards by headphones and pinna (i.e. no headphones is measured. As seen above, to get one impedance measurement, three pressure points must be taking into account. The headphone is not moved during the three pressure points analysis. Once the impedance is obtained, the process is repeated without any headphone displacement. If the new impedance is the same as the previous one, it is considered right. If not, two new measurement are made until they are the same.

Once it happens, the headphone is moved in order to see the replacement sensibility and a new measurement process (the paragraph above) for the same device starts. Three different measurements of left and right side headphone are performed. When the six measurements are over, a new headphone model is placed at the end of the tube. Twenty five different models are considered (Table 1).

The measurements do not take place in any special equipped room. It is known for previous experiments that this fact does not distort the obtained measurements ([5]). The measurements are carried out using the software *Monkey Forrest* (*MF*) developed by ITA (Aachen, Germany).

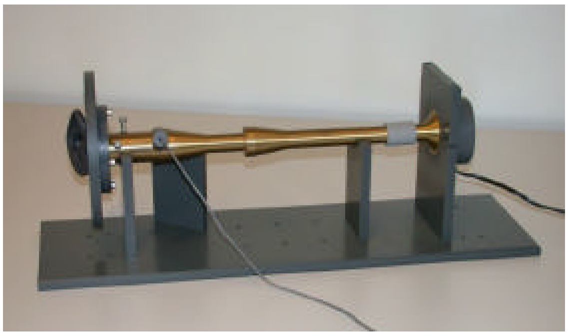

Figure 2: Impedance tube with the pinna in its end.

2.3. Tested Headphones

The whole list, as well as some of their characteristics, is shown in Table 1.

Ref.	Model	Type	Openness
01	Sennheiser HD-25-SP	Supraaural (S)	Closed (C)
02	Senn. HD 580 Precision	Circumaural (C)	Semi-opened (SO)
03	Senn. HD 250	C	SO
04	Senn. HD 600 Avantgarde	C	SO
05	Senn. HD 270	C	C
06	Senn. HD 490	S	SO
07	Senn. HD 570	C	SO
08	Senn. HD 495-I V1	S	SO
09	Senn. MX 300	Intraaural (I)	
10	Senn. MX 400	I	
11	Senn. MX 500	I	
12	Senn. HD 280 Pro	C	C
13	Senn. HD 477	S	SO
14	Senn. HD 497	S	SO
15	Koss R80	C	C
16	Beyerdynamic DT 770	C	C
17	Beyerdynamic DT 770	C	C
18	Sony MDR CD 780	C	SO
19	Beyerdynamic DT 911	C	SO
20	Quart Phone 280	C	SO
21	Quart Phone 200	C	SO
22	Beyerdynamic DT 880	C	C
23	Sony MDR-60 II	C	SO
24	Stax G845	C	Opened (O)
25	Stax G846	C	O

Table 1. Headphones and their characteristics.

Circumaural headphones are those which rounds the whole ear. Supraaural headphones have a plate shape placed on the ear, and intraaural ones are sited inside it (normally used with 'walkman' devices). The openness column defines how much sound the headphone leaves to go out, e.g., a person with a closed headphone is not able to hear anything but the sound performed inside.

3. IMPEDANCE RESULTS

In the this section, some figures from impedance measurements are shown. Once every value is obtained, it is compared with the pinna, or free space, impedance. This has been also measured using the same method but without any headphone. The impedances shown in plots correspond to the *m* factor, defined in equation (1.6).

3.1 Replacement sensibility

How the impedance changes when the same headphone is replaced over the ear is an important point and it is an absolutely normal event. These changes speak about the accuracy of the process itself.

Intraaural microphones show the greatest changes when replacement happens. Figure 3 presents the three left impedances obtained with an intraaural model. Maximums are displaced and their values are significantly different. It can be considered as logical if it is noticed that this kind of headphones block absolutely, but in a different way each time, the auditive canal.

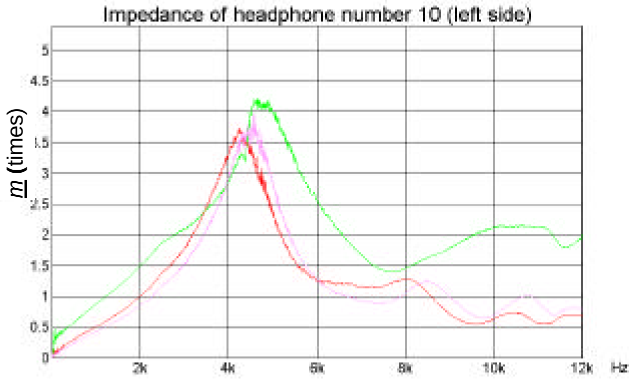

Figure 3: Replacement sensibility in headphone '10' (intraaural)

With the other headphone types, the measurements are much more similar, either along the frequency shape or the offset which does exist in Figure 3.

3.2 Intraaural Headphones

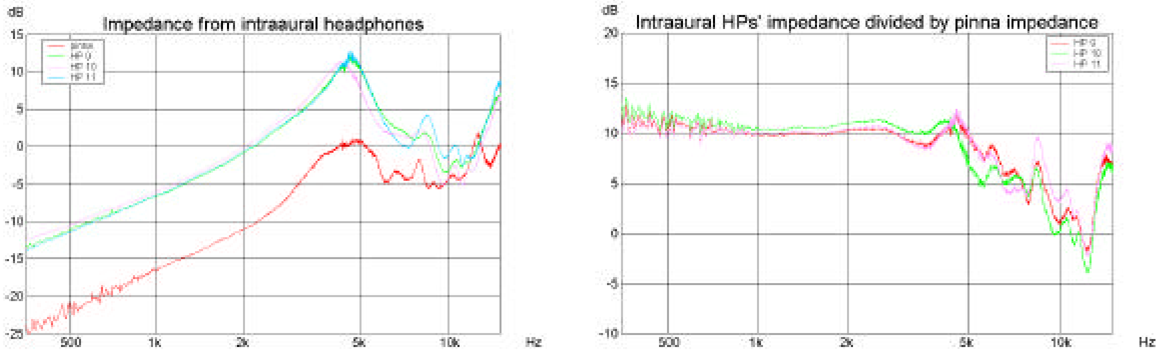

Figure 4: Intraaural headphones impedance (m). Absolute and relative to pinna value.

Figure 4 shows again the expected behaviour. Intraaural headphones have the greatest differences in comparison to the free ear situation ('pinna' plot). The impedance shown by these headphones is much higher since the ear canal is completely blocked. This difference is higher at lower frequencies and a constant 10 dB offset can be detected. This offset lasts until 3 kHz, and then the difference between impedances gets low and fluctuates.

3.3. Open And Semiopen Headphones

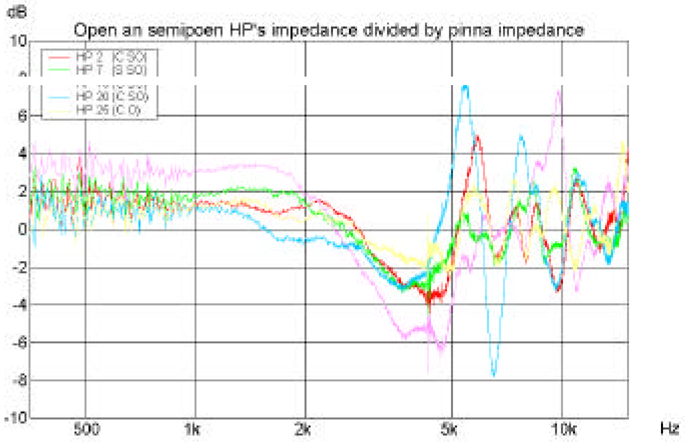

Figure 5: Open headphones (related to pinna-free space value)

Impedance from open and semi-opened headphones is the most likely to the free ear situation. This is because this kind of headphones does not close the ear so much. It is also possible to observe an offset at low frequencies. This offset is not so big as intraaural models and it is in a range from 1 to 4 dB until 2 kHz, but it changes between headphones. The offset from supraaural headphones is higher than from circumaural headphones.

3.4. Closed Headphones

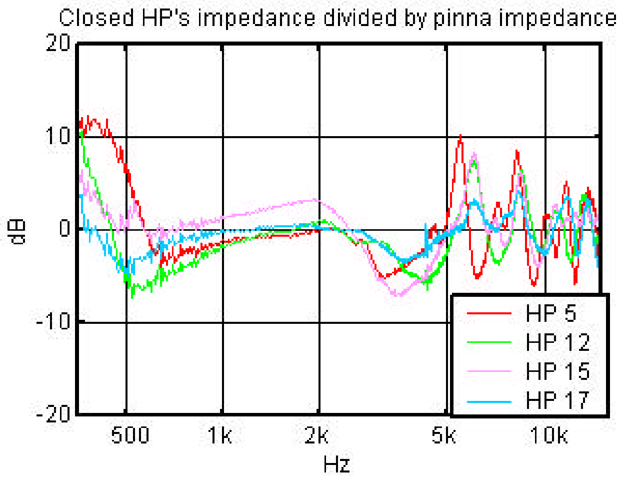

Figure 6: Closed headphones (relative to pinna-free space value)

It can be seen in Figure 6 that the dips in these graphs are quite high and, in general, the impedance is quite different from the free ear situation. That is due to the ear's closing which provokes this kind of differences. They are more extreme than in open or semi-opened headphones. It is not possible to perceive any offset in this set of headphones.

4. CONCLUSIONS

Impedance results can be classified depending on the headphone openness, but not with the type. Impedance from opened and semi-opened models, as well as intraaural headphones, show an significant offset relative to the pinna impedance at low frequencies. Besides, the replacement sensibility takes importance again with intraaural models, which quite different impedance values are reached in. Even when it happens with other headphone types, it is not so important.

Regardless of there are some models quite different from the free ear situation, others are very similar to that situation. These should be used in later tests checking psichoacoustical differences when the sound performing is implemented with headphones and some other ways (while keeping the ear conditions).

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