IS THE SOUND WE HEAR 'REAL'?

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01. INTRODUCTION

As a way of perceiving the world, we are constantly accessing sound. However, for sound emitted by the same source, does everyone hear exactly the same sound? Actually, the size and mass of the head, the shape and position of the ears, and the dimensions of the oral cavities all manipulate the incoming sound waves by boosting some frequencies and attenuating others. These variations in the frequencies and amplitudes of a sound contribute to the audience's distinct perspective and experience. Past scholars used the term HRTF (head-related transfer function) to describe how are the sound people receive different from the source. In this project, we decided to focus on the effect of the length and the diameter of the ear canal on the sound we listen to.

We simulated different ear canals with different lengths and diameters of headphone front cavities, measured the frequency response curves of samples with artificial ears and attempted to explain the phenomena using the theory of electroacoustic analogy.

FIG.1 HUMAN'S EAR

03. Methods

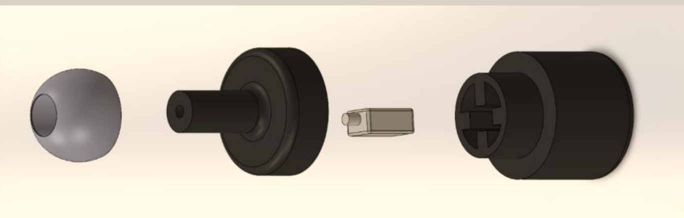

FIG.2 IEM STRUCTURE

IEM stands for in-ear monitor, containing a front cavity that can be modelled as the ear canal.

Shown in Figure 2 is an IEM built by us through 3D printing. It mainly comprises an earplug, a replaceable front cavity, Knowles -29689 balanced armature unit, and a back cavity. We printed 12 different front cavities to simulate different ear canal sizes, specifically with diameters of 2.5mm, 3mm, 3.5mm, 4mm, and lengths of 15mm, 20mm, 25mm.

We used an IEC-711 artificial ear coupler to measure the raw data. We connected the headset and the artificial ear to the computer through a sound card, using the headset as an output to produce sound and the artificial ear as a microphone to receive signals.

About the analysis software, we used the Room EQ Wizard, which would automatically generate the output and analyze the received signal to generate the frequency response curve of the tested product.

FIG.3 SET UP OF EXPERIMENT

04. CONCLUSIONS

In conclusion, as the size of the aperture increases, the resonance peaks occur at a higher frequency and at a higher intensity. On the other hand, an increase in the length of the tube in which the air column passes will cause resonance to occur at a lower frequency. In practical applications, the effect of the ear canal on sound should also be considered. For example, a noise of 2kHz will affect a person more than measured because of the enhanced resonance that occurs in the ear canal. Finally, as Dr. Walter Lewin famously said, any measurement is useless without the knowledge of its uncertainty. The main uncertainties come from the experimental set-up as well as the apparatus used. In the low-frequency range (<100Hz), the curves obtained were not smooth as the sound input was corrupted by the ambient surrounding noise since the measurements were not taken in a strict silencer chamber. The artificial ear used, known as the iec711 coupler, is not verified to simulate the human ear at frequencies above 10kHz, and so the readings above this point are inaccurate and should not be considered.

02. DATA ANALYSIS

Before discussing our experimental results, we must first discuss what exactly SPL and frequency response are.

Sound pressure response, or SPL, is a widely acknowledged measure of the strength of an acoustic wave. It is designed such that the output values match the threshold for human hearing at ~1000Hz for a young person.

Since we experience noise on a logarithmic scale, this is achieved by defining SPL as

$$SPL=20\log(P/P_0)$$

Where P is the sound pressure of the noise and P0 is defined as the reference pressure, 2×10^(-5) Pa [1].

Figure 4 is about SPL we measured from IEM with tube diameter 3.5mm and lengths 10mm, 15mm, and 20mm. Figure 5 is the SPL of IEM with a tube length of 15mm and diameters of 2.5mm, 3mm, 3.5mm, and 4mm. As the measurement errors of the latter two peaks were so large, there was little point in discussing them. Thus, we mainly focus on the differences between the first peaks. There are two main findings: the resonant frequencies in the tube decrease as the inner diameter decreases and the length increases; the amplitude of the detected sound at resonant frequencies decreases as the inner diameter decreases and as the length increases. Now let's explore the reasons for this phenomenon.

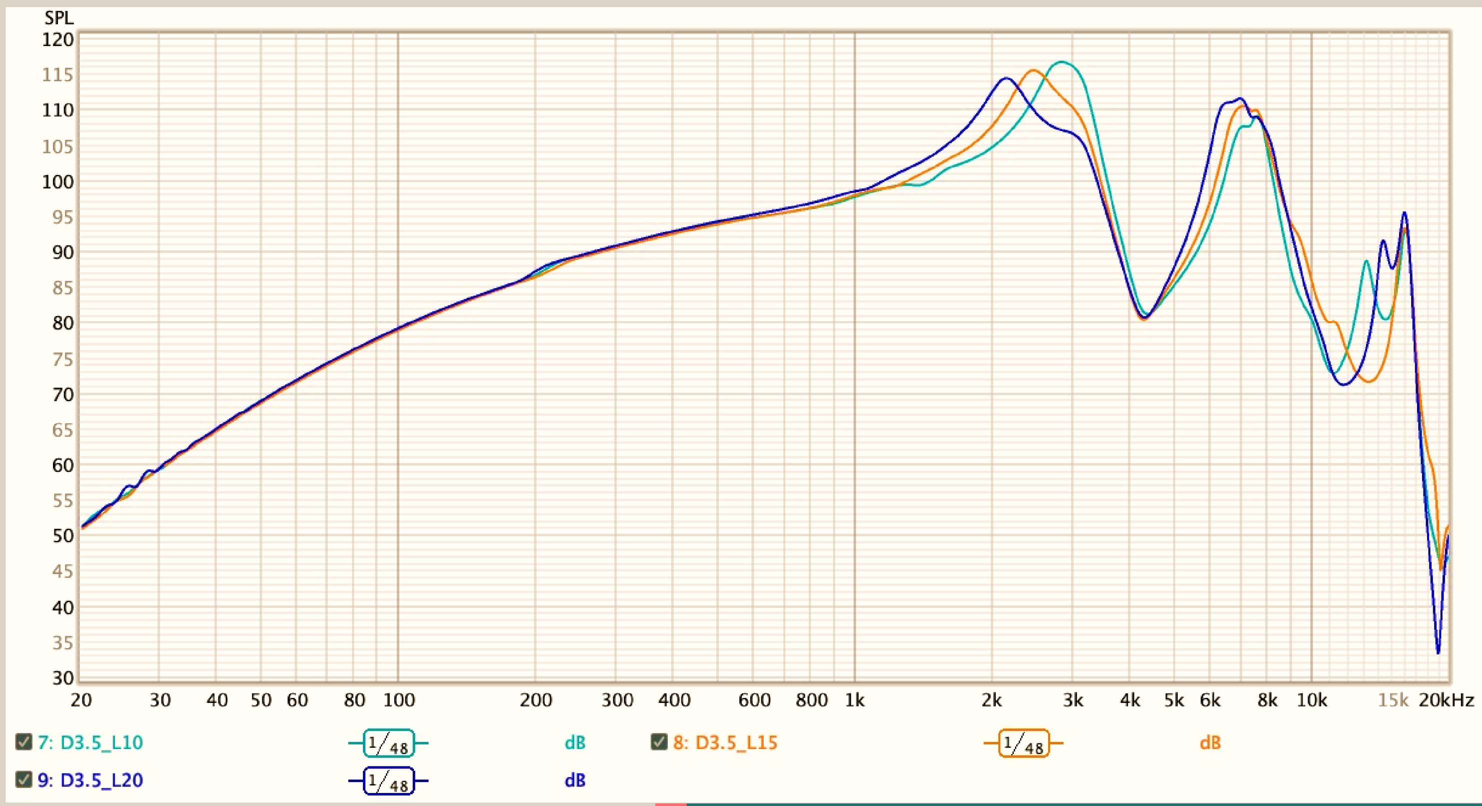

FIG.4 Outputted curves of different lengths of IEM

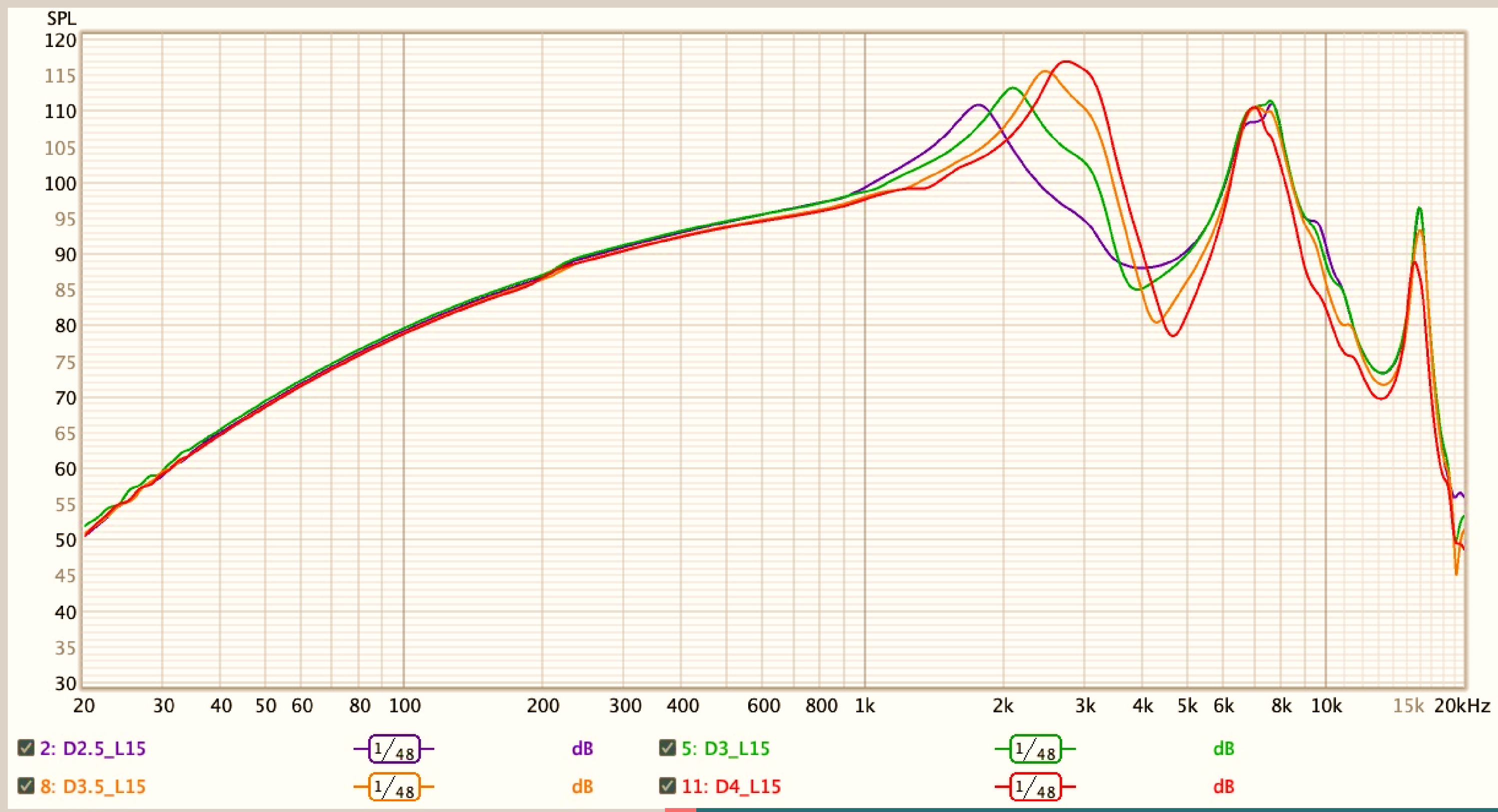

FIG.5 Outputted curves of different inner diameters of IEM

THEORY

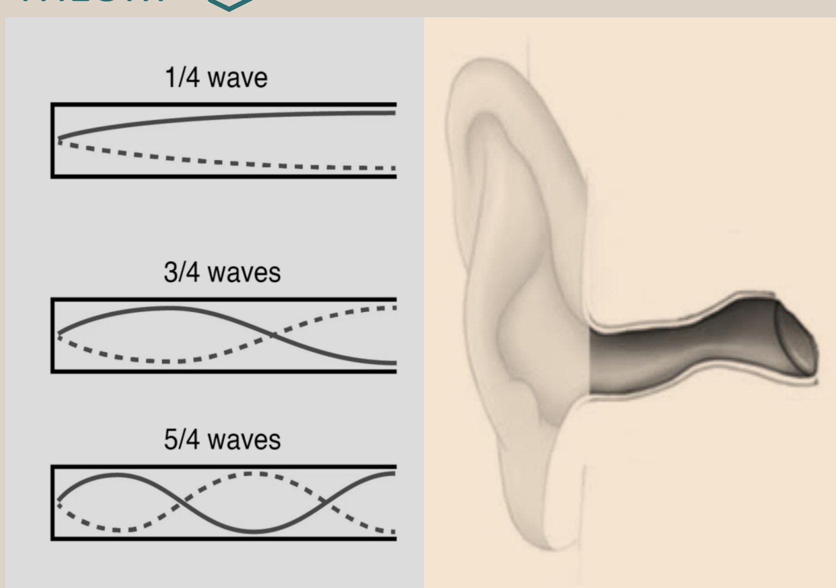

FIG.6 RESONANCE IN EAR CANAL

EFFECT OF LENGTH ON RESONANT FREQUENCY

The first thing that you may notice is that there seem to be three resonance peaks in each diagram. This can be explained by the normal modes theory of standing waves. The sound wave can be thought of as being fixed at two ends, one at the diaphragm of the speaker and the other at the end of the ear canal. This means that the sound wave should show resonance at regular intervals of

$$\lambda = \frac{2L}{n}$$

With n being the n-th mode. With our apparatus, the diaphragm can be seen as being located at the front of the ear canal, thus L is simply the length of the ear canal.

SOUND-ELECTRICITY ANALOGY

Sound has acoustic resistance(Ra), acoustic capacitance(Ca) and acoustic inertance(Ma). By modelling the ear canal as a Helmholtz resonator, we were able to treat it as either an RC circuit or an LC circuit, where quantified calculations can take place. In this case, Ra, Ma, and Ca can be found as follows:

$$\bullet R_a = \frac{\rho\sqrt{2\eta\omega}}{\pi r^2}\left(\frac{1}{r}+2\right); M_a = \frac{\rho L}{S}; C_a = \frac{V}{\rho c^2}$$

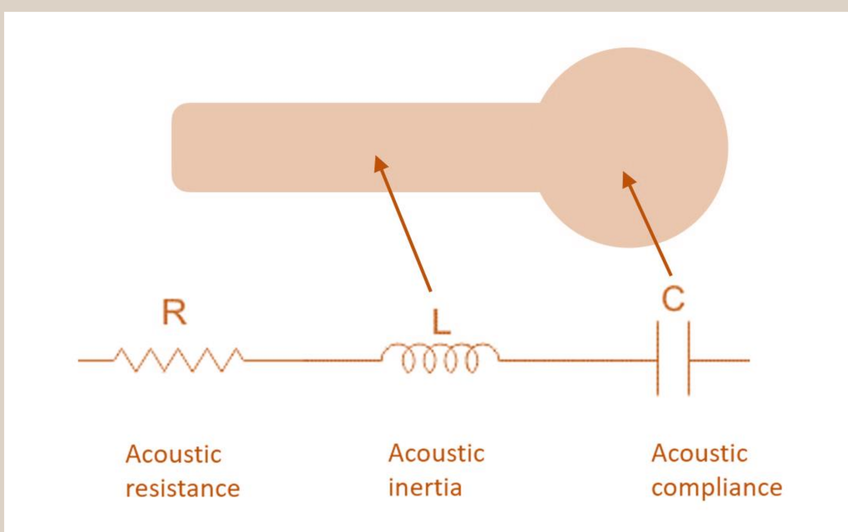

FIG.7 HELMHOLTZ RESONATOR

If we regard an ear canal as the body of the bottle, the circuit turns from an LCR to a CR circuit. In this case, the RC circuit acts as a low-pass filter. The gain of this circuit is described by the equation: $Gain = \frac{1}{\sqrt{1+(\omega RC)^2}}$

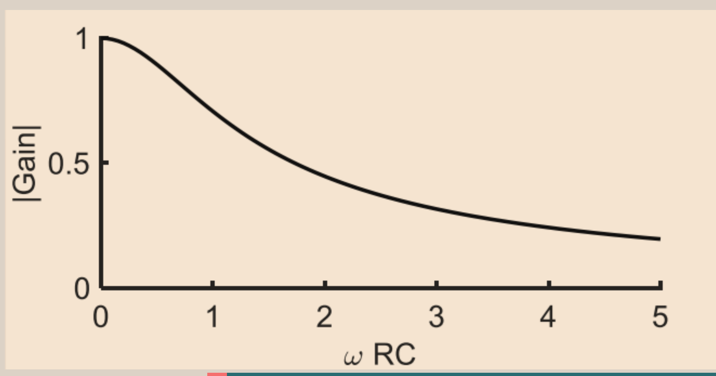

FIG.8 GAIN CURVE

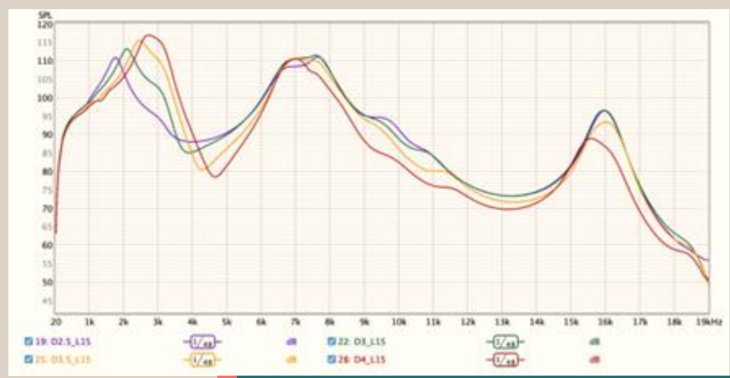

FIG.9 SPL CURVE IN LINEAR SCALE

As you can see from Figure 8, at low frequencies, the gain the close to one. This means that all outputs should be constant. This is reflected in the superimposition of the low-frequency regions of the SPL curve. At the same time, RC is proportional to the length and inversely proportional to the radius. This means that as the length of the headphone increases, the time constant increases, and so after the initial relative constant region, the Gain vs ωRC curve decays faster. As the radius increases, RC falls and so the curve decays slower.

If we assume that acoustical energy is wholly conserved, thus theoretically making acoustical resistance zero. With this condition in place, the LCR circuit becomes an LC circuit.

The resonant frequency of an LC circuit can be found at: $f_0 = \frac{1}{2\pi\sqrt{LC}}$

Plugging in the equation for Ca and Ma gives: $f_o = \frac{1}{2\pi}\sqrt{c^2\frac{S}{Vl}}$

When the diameter of the earphone increases, thus CSA increases, the resonance peaks occur at a higher frequency, which is shown by the rightward shift in the peaks shown in the diagram of changing diameter. On the other hand, as the length of the earphone increases, modelling an increase in the length of the ear canal, the frequency at which resonance occurs decreases. The overall behaviour of the ear canal is the superimposition of both of these effects, which was the trend observed. Our analysis focused mainly on the first instance of resonance. In ideal theoretical conditions, the later peaks would follow the same trends.

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