# Overview of Headphones

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## 1 Introduction

As Cambridge dictionary defines - Headphones are a device with a part to cover each ear through which you can listen to music, radio broadcasts, etc. without other people hearing. Even though the first early ancestors of headphones were used by telephone operators and were not used for any music related applications, nowadays headphones became a crucial part of the music industry.
While headphones function the same way as speakers, the produced output is far too different. While speakers are supposed to generate a powerful sound signal for it to be audible, headphones only require to generate a weak enough signal which needs to reach the eardrum which is only a few millimeters away. Therefore components used in headphones are much smaller and most of the time more precise than speaker components. Small distance and isolation are the two main contributors to the loudness of the sound even when the signal is relatively weak in comparison to regular speakers. Most headphones even support the full 20 hertz to 20,000 Hz frequency range. However, not all of them can produce a proper low frequency signal since it requires to move a large amount of air.
The report submitted by Grand View Research, Inc. states that the global earphones and headphones market is expected to reach 17.55 billion USD by 2022, which shows, that the demand for new products, better quality and reliability is constantly increasing.
This paper reviews the overall history headphones, specifies the types of headphones and their transducers and shows how an isodynamic headphone can be designed and simulated using equivalent electrical components. The simulation results are discussed and are used to show to importance of proper simulations and parameter choice.

## 2 History of Headphones

It is rather difficult to determine when the first headphones were developed, because there was no strict difference between a speaker near your ear and a single earpiece. It is believed that the first headphones were born in the 1880s, which were a single earpiece that rested on the user's shoulder and weighed over 10 pounds. However, as mentioned before, with this weigh it is more likely that this earpiece can be defined as a boombox on your shoulder rather than a headphone.
In 1910 US Government bureau, Radio Division received a letter from Nathaniel Baldwin. The writer, Mr. Baldwin stated that he was sending a pair of telephones, which he had patented, and requested that they be tested [2]. He wrote that they had a resistance of about 2,000 ohms, which he understood was standard for Navy headsets [2]. As stated in the book, this was the beginning of low weight, adequate quality headphones with stable impedance. With the help of the Wireless Specialty Apparatus Co. these headphones were manufactured not only for the US Navy, but also for the civilian market.
The first dynamic headphones that hit the market were Beyerdynamic DT-48. They are demonstrated in Fig. 1.


**Figure 1:** *The historical Beyerdynamic DT 48.*
https://beyerdynamic.com

This was an important milestone in the history of headphones since even now, dynamic headphones are the most popular type on the market. Another mention worthy creation were Koss SP-3, the first stereo headphones which were released in 1958. Due to this product Fig. 2 Koss dominated the industry for a few decades.

1979 was the year, when Sony showed that the headphones can and had to portable. This year is the release of Sony Walkman series were MDR-3L2 headphones were included.

**Figure 2:** *SP/3 The World's First Koss Stereophone*
https://www.koss.com/history

The 80's and 90's brought a bunch of solutions from earbuds and in-ear headphones to neckband headphones which lost their popularity quite fast while in-ear headphones and earbuds are one of the most popular types nowadays. At the beginning of a new century, Bose presented their QuietComfort line which came with active noise-cancelling technology. Even though the concept itself was not new to the world, although not too many products were available on the market.
One of the biggest game changers in the music universe was the release of iPod. Since 2001 it became common to people with a white cord running from their pocket to their ears. From the release up to today over 300 million iPods have been sold and obviously the same amount of earbuds as well. Throughout the time after different designs and types flooded the market and nowadays users can choose from a variety of different headphones with different price ranges, quality and additional features which shows, that even this invention comes from the past, the relevance of it stays on and increases over-time.

## 3 Headphone types

Nowadays headphones can come in many sizes and shapes to best fit the users preferred experiences. Their appearance affects the balance between portability and fidelity. In general, headphone can be divided into four different types:

### 3.1 Circum-aural headphones

Over-ear headphones, full size headphones or circum-aural headphones have elipsoid or circular earpads that encompass the ear. Usually considered the best headphones for sound quality. Circumaural headphones are characterized by a relatively large coupling volume in excess of 30 cubic centimeters, and an inner diameter of the cushions of at least 55 mm [1]. Due to complete surrounding of the ear, these headphones can be designed to passively attenuate as much outer noise as possible. The main drawback comes from their size, which may result in them being heavy and uncomfortable to the user. Usually their used by drummers or in the recording studios.

### 3.2 Supra-aural headphones

On-ear or supra-aural headphones are similar in design to over-ear models, though the cushions sit on the outer ear rather than enclosing the ears. Generally, over-ear models deliver adequate sound quality, but with less bass response compared to over-ear models. Even though this type weighs less than over-ear they can still lead to user discomfort due to pressure on the ear itself.
Both supra-aural and circum-aural headphones can be closed-back, semi-open or open-back. The open-back headphones gives a more natural, ambient sound while closed-back headphones produce a stronger bass response and better attenuates ambient noise.

### 3.3 Earphones/earbuds

Earphones are very small headphones that are directly fitted on the outer ear. The difference between IEMs (In-ear monitors) are that they are only facing ear canal, but are not inserted into it. Even though earphones may be considered as the cheapest type of headphones, they are usually not too comfortable and provide close to no audio isolation. They are the most common types of headphones to be found included with MP3 players or other music devices and phones.

### 3.4 Intra-aural headphones

In-ear headphones/monitors are small headphones that are directly inserted in ear canal. Most models include silicone or foam tips in multiple sizes which gives a secure fit and proper ambient noise isolation. Due to fully blocking the ear canal, they are considered the best noise-cancelling headphones. IEMs can be considered as better quality in-ear headphones. Usually they come with multiple drivers and are used by audio engineers, audiophiles and musicians.

# 4 Types of Transducers

While headphone types are an important aspect for the listener and overall headphone experience, the main part of the headphone is its transducer. Transducers job is to convert the electrical signal into a sound wave that the ear can understand. Transducers use several technologies which includes manipulation of magnetic, electric or magneto-electric fields to create a sound wave. Even though the first headphones used only a single type of a transducer to achieve its goal, nowadays multiple types of transducers can be used to achieve even better results, however, badly designed quad-driver headphones can sound far worse than a single driver headphones. Currently there are quite a few types of transducers on the market and even more are developed, most of them can be defined as those, mentioned below:

## 4.1 Dynamic transducers

Dynamic or moving-coil transducers are the most common transducers on the market due to its low manufacturing price. The transducer consists of three parts: a magnetic element which creates a static magnetic field, a voice coil and a diaphragm which is attached to the voice coil. When a current runs through the voice coil it creates a magnetic field which may be opposite or the same in direction to the stationary magnetic field. Due to varying magnetic field of the coil the coil itself gets attracted or repelled by the magnet which causes the coil and the diaphragm to vibrate. The vibrating diaphragm displaces the air around it, creating sound waves. Obviously, the larger the air displacement, the higher the volume. Because of that, dynamic headphones are great at creating the bass response and transducers are popularly used in multiple driver headphones to handle the lower frequency sounds. The down-side of the transducer is its non-linearity at high volumes, however this can be mitigated by properly designing the transducer and using it in its linear region.

## 4.2 Balanced armature transducers

Balanced armature is a sound transducer primarily designed to reduce the stress on the diaphragm and increase the overall electric efficiency. It consists of a miniature armature inside a coil surrounded by two magnets. The basic mechanism of this transducer is present in Fig. 3.

When current flows through the coil, it magnetizes the armature which pivots towards one or the other magnet. This pivoting movement causes the movement of the diaphragm which produces the sound. The term "balanced" comes from the fact, that when no force is applied to the armature it stays at the exactly same distance from both magnets, hence it is balanced. The common practice is to use this type of transducers for certain frequency range to achieve better overall response. As

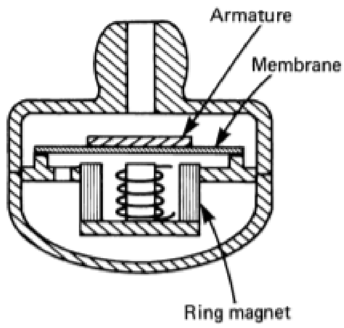



**Figure 3:** *Mechanism of a balanced armature transducer [1]*

mentioned above, balanced armature transducers are commonly used with dynamic transducer since they commonly lack proper bass response. The advantages of this type of transducers are more detailed sound and better treble performance than dynamic transducers, however, they lose in manufacturing price and complexity as well as bass response.

### 4.3 Electrostatic transducer

While other types of transducers use electromagnetic properties to create sound, as the name implies, this type of transducer uses static electricity as its main property to produce mechanical waves. Transducer consists of a thin electrically charged diaphragm which is suspended between two perforated electrodes Fig. 4.

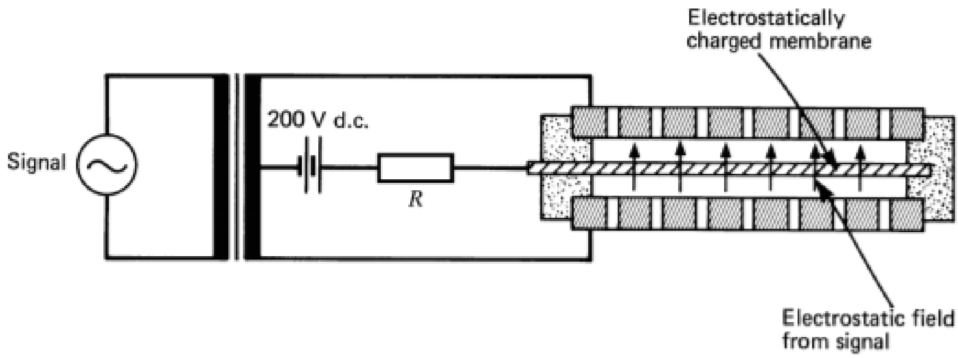



**Figure 4:** *Electrostatic transducer diagram* [1]

When an electrical signal is applied to the electrodes it creates an electric field which attracts the diaphragm to one of the plates. The constant change in the electric field vibrates the diaphragm which moves the air through the perforated gaps which results in a sound wave. The diaphragm is manufactured as light and as flexible as possible. As mentioned in [4] the wavefront is nearly plane at all frequencies so that small changes of position or distance make little difference to the sound pressure.

Additionally, the frequency response of this type of transducer usually extends above the audio frequency limit which results in lower distortion throughout full audio range and more accurate response at higher frequencies which is usually absent at dynamic drivers. The electrostatic principle has inherent advantages which make possible the construction of loudspeakers with lower coloration, better transient response, lower non-linearity distortion, and radiation characteristics more suitably related to room acoustics, than can be achieved using other techniques [1]. However, the manufacturing complexity for this type of transducer reflects on the higher price of the headphones, furthermore, the headphones are usually pretty large and bulky, since the driver itself is usually made quite large to deliver proper sound. Furthermore, electrostatic drivers require special amplifiers, since voltages up to 1kV are required to deflect the membrane. Even though some may think, that this type of transducer should be unsafe to the user due to high voltages, it is not actually correct, since the isolation and the low amount of current needed for this transducer makes it as safe as possible for usage. All in all, electrostatic transducers may be seen as the best type of transducers for a high-end headphone set, however due to its high price and bulkiness they are not the most preferable pick.

### 4.4 Planar magnetic transducers

Planar magnetic transducer or also known as orthodynamic (Yamaha) transducer is based on a similar principle as a dynamic transducer, but instead of the moving-coil that is affected by magnetic field change the full diaphragm is affected to produce sound. In design it is somewhat similar to electrostatic transducers, the diaphragm contains an embedded wire pattern and is located between two or more permanent magnets. The current running through the pattern creates a magnetic field which reacts with the magnetic field of the permanent magnets which induces vibrations and hence - sound. Since the whole diaphragm has to be evenly vibrated, larger magnets are needed to create the best response Fig. 5.

For this reason, this technology is relatively large in size, compared to moving-coil transducers and also quite expensive. However, this type of transducer creates a high quality sound with close to no distortion and a good transient response. Additionally, bass response is excellent, due to the combination of the large thin diaphragm and strong electromagnetic force leading to the ability to displace a large amount of air and creating proper low frequency sound wave. Nevertheless, great sound reproduction comes with a few drawbacks. Thin diaphragm has a higher manufacturing price, also two large magnets are required as well which makes headphones with this type of transducer relatively heavy and not popular to be used in portable applications, additionally, most transducers require an additional amplifier due to its high impedance.

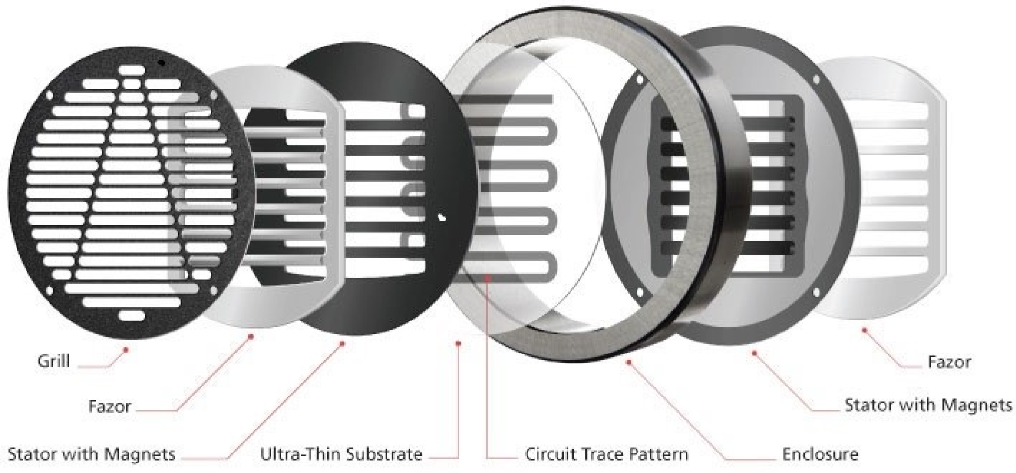



**Figure 5:** *Planar magnetic transducer* (Audeze planar driver unit)

# 5 Electrical analogies for headphone modeling

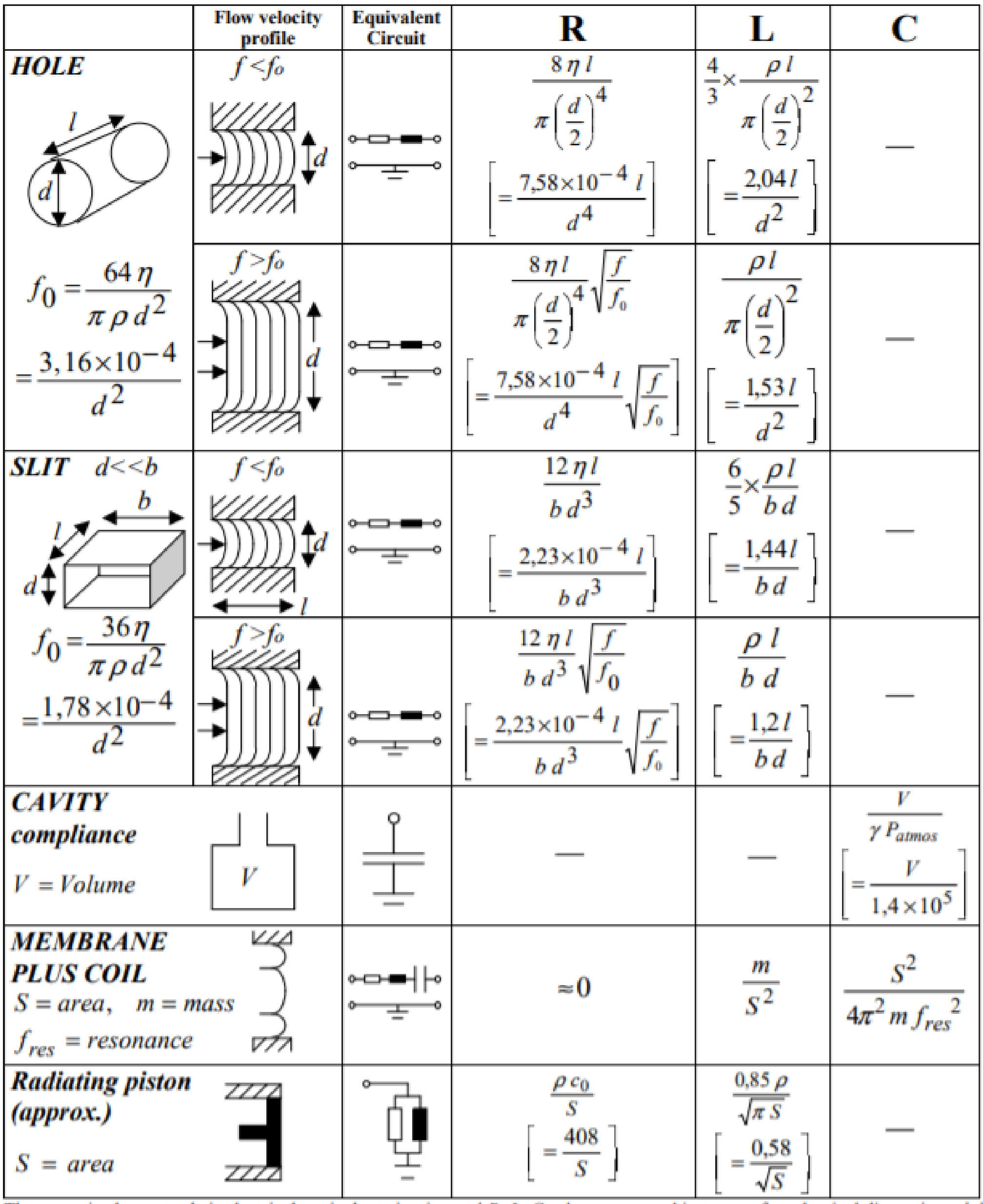
In the previous chapters the physical appearance and the type of transducers were discussed, but the main question comes - how is it possible to model such a complicated electromechanical system. According to [1] headphones comprise of mainly these building blocks:

## 5.1 Cavities

Cavities are modelled as a single capacitor connected in parallel to the system and additonally one of the nodes is always grounded. Cavity is defined by its volume and the formula presented in the Fig. 6 defines the capacitance.

## 5.2 Acoustical bottlenecks - holes and slits

Due to simple manufacturing, porous elements like holes and slits are used for resonance damping in headphones. However, when simulating holes or slits, the frequency dependency comes as a factor and it changes values L and R even though in their electrical counterparts, these values are usually frequency independent and only the impedance of the inductance changes with the frequency. As seen from Fig. 6, L value changes at the frequency crossover point and when the frequency is bigger than f0 R becomes fully frequency dependent at different frequencies and not only in a single range. This makes the simulations a bit more complex and various solutions have been proposed to simplify the system which will not be discussed in this paper.



| | Flow velocity profile | Equivalent Circuit | R | L | C |
|---|---|---|---|---|---|
| ***HOLE*** | $f<f_0$ | | $\frac{8\eta l}{\pi\left(\frac{d}{2}\right)^4}$ $\left[=\frac{7{,}58\times10^{-4}\,l}{d^4}\right]$ | $\frac{4}{3}\times\frac{\rho l}{\pi\left(\frac{d}{2}\right)^2}$ $\left[=\frac{2{,}04\,l}{d^2}\right]$ | — |
| $f_0=\frac{64\eta}{\pi\rho d^2}$ $=\frac{3{,}16\times10^{-4}}{d^2}$ | $f>f_0$ | | $\frac{8\eta l}{\pi\left(\frac{d}{2}\right)^4}\sqrt{\frac{f}{f_0}}$ $\left[=\frac{7{,}58\times10^{-4}\,l}{d^4}\sqrt{\frac{f}{f_0}}\right]$ | $\frac{\rho l}{\pi\left(\frac{d}{2}\right)^2}$ $\left[=\frac{1{,}53\,l}{d^2}\right]$ | — |
| ***SLIT*** $d<<b$ | $f<f_0$ | | $\frac{12\eta l}{b d^3}$ $\left[=\frac{2{,}23\times10^{-4}\,l}{b d^3}\right]$ | $\frac{6}{5}\times\frac{\rho l}{b d}$ $\left[=\frac{1{,}44\,l}{b d}\right]$ | — |
| $f_0=\frac{36\eta}{\pi\rho d^2}$ $=\frac{1{,}78\times10^{-4}}{d^2}$ | $f>f_0$ | | $\frac{12\eta l}{b d^3}\sqrt{\frac{f}{f_0}}$ $\left[=\frac{2{,}23\times10^{-4}\,l}{b d^3}\sqrt{\frac{f}{f_0}}\right]$ | $\frac{\rho l}{b d}$ $\left[=\frac{1{,}2\,l}{b d}\right]$ | — |
| ***CAVITY compliance*** *V = Volume* | V | | — | — | $\frac{V}{\gamma P_{atmos}}$ $\left[=\frac{V}{1{,}4\times10^5}\right]$ |
| ***MEMBRANE PLUS COIL*** *S = area, m = mass* $f_{res}$ *= resonance* | | | $\approx 0$ | $\frac{m}{S^2}$ | $\frac{S^2}{4\pi^2 m f_{res}^2}$ |
| ***Radiating piston (approx.)*** *S = area* | | | $\frac{\rho c_0}{S}$ $\left[=\frac{408}{S}\right]$ | $\frac{0{,}85\rho}{\sqrt{\pi S}}$ $\left[=\frac{0{,}58}{\sqrt{S}}\right]$ | — |

**Figure 6:** *The acoustic elements, their electrical equivalent circuits, and R, L, C values expressed in terms of mechanical dimensions: l, b, d(m),* $S(m^2), V(m^3), frequency f(Hz)$[3].

### 5.3 Membranes

Mebrane is usually represented as a series connection of RLC components. These acoustic parameters are related to the mechanical ones Rmech, Mms, Cms [1]. One of the most reliable ways to obtain these parameters for a moving-coil transducer is to use Thiele-Small procedure. From Fig. 6 we can see that R is normally negligible in this case except for some special cases, where it is deliberately cultivated using sandwich membranes with adhesive between [1].

### 5.4 Radiation impedances

Due to the fact, that most headphones cannot be entirely closed, radiating components appear due to openings or leaks. These are represented in the first approximation by a parallel combination of R and L connected to ground, which is rigorously true only for a spherical zero-order source [1]. At high frequencies the real component R predominates and represents the radiation energy loss. Similarly to holes and slits, this component can be used for resonance damping as well. At low frequencies the radiation impedance becomes reactive and is equivalent to a mass loading [1]. In most approximations due to low radiation given circuit can be replaced as a short circuit due to its negligible effect.

## 6 Isodynamic headphone circuit simulation

For example purposes a simple schematic of an isodynamic headphone was chosen. The purpose of these simulations is to show how the frequency response may shift when some parameters, which resemble a certain characteristic, are changed. The schematic design and simulations were made using LTspice XVII software. The elements in Fig. 7 define: Rr and Lr - radiation impedance, Lm and Cm - membrane, C0 - dominant acoustic compliance of the air, R0 and L0 - leak impedance, Rh - porous resistance, C1 - cavity compliance. Note, that the schematic does not include transduction element, since only the frequency response is simulated and not an SPL (Sound pressure level).

Note, that the given schematic with lumped elements represents a proper frequency response up to 5kHz. Due to the inhomogenity of the sound field, the response at higher frequencies is not accurate. However, these simulations are useful to demonstrate the main features of certain blocks and how they interconnect. The results of the simulations are presented in Fig. 8.

The first curve (green) shows how a frequency response would look like without the radiation resistance and when no porous resistance is present (headphone with no holes or slits). A really high resonance peak displays an electrical equivalence of a high quality resonator. This peak can only be seen with perfect induction and

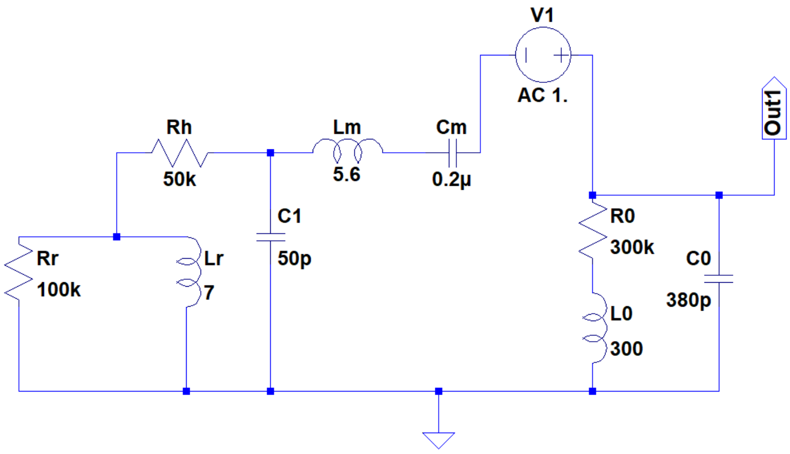



**Figure 7:** *The schematic of an isodynamic headphone.* Example taken from [1]

capacitance elements (no parasitic properties), however, this is highly unrealistic and gives improper results. The second curve (blue) shows how the frequency response changes when a normal radiation impedance is present. Due to radiation losses, the quality of the resonant circuit is smaller and the resonant peak is wider and lower. This presents a more realistic case of a headphone frequency response and presents the importance of a proper and full modelling. The third curve (red) represents the frequency response of the original circuit that is presented in Fig. 7. The lowered resonance peak compared to the second simulation shows how a simple hole in the headphones can be used to modify the frequency response to achieve desired results. And the fourth curve (yellow) represents how an increased membrane stiffness affects the lower frequencies if other parameters would remain the same. This shows, that even a small change while manufacturing certain headphones can easily transform the designed frequency response and add unwanted attenuation or additional frequency response changes which are usually highly unwanted.

## 7 Conclusions

In this paper, the history of headphones was presented while showing significant changes that affected the way headphones are perceived now. The most common types of headphones and transducers were presented, which shows that no single solution is best in terms of listeners perspective. Additionally, a simple overview of how headphones are modelled was presented with an example which shows, how certain parameters affect the full response and how simplifying the simulation circuit can give a very different and unrealistic result than it was expected. As mentioned in the introduction, this only an overview of how headphone modelling is done and even here it can be seen, that the complexity of this topic is quite significant and requires proper analysis and research to fully understand it.

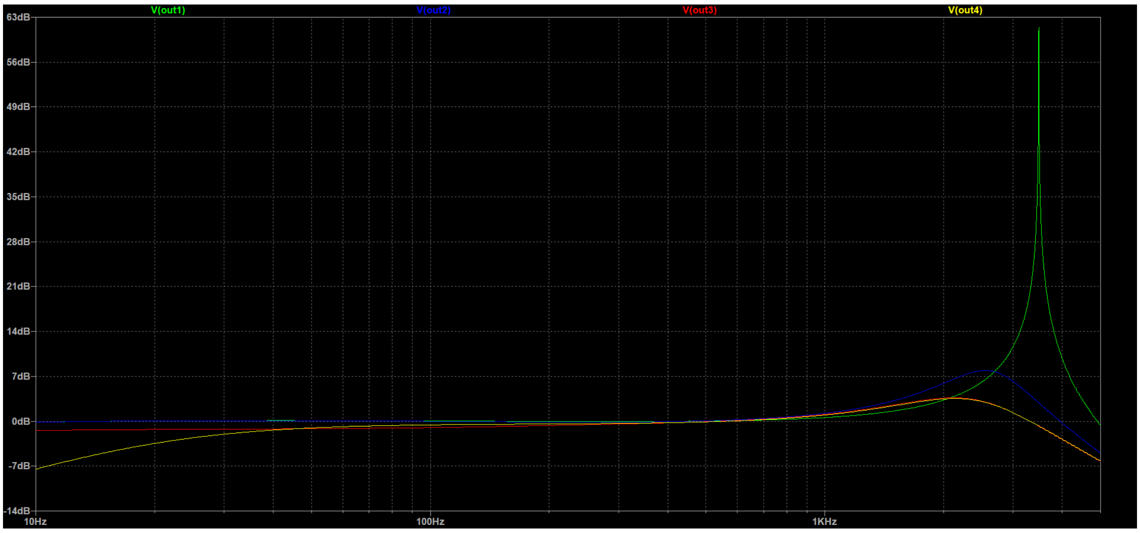



**Figure 8:** *Simulation of the schematic with changed parameters Green - Rr=Rh=0, Blue - Rh=0, Red - original, Yellow - Cm=0.025uF*

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