

Using tubephones for wideband auditory stimulation in brain research

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Summary

There has been a need of a high quality wideband auditory stimulation system for brain research purposes. Magnetic imaging techniques such as functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) do not allow the use of typical headphones. One possible approach is to place electromagnetic transducers outside of the shielded measurement room and transmit the sound to the patient's ears by flexible sound tubes, which produce a highly distorted frequency response due to the tube resonances. In this paper it is shown that by combining acoustical design with analog and digital equalization, wideband flat frequency response is achieved.

1. INTRODUCTION

Functional magnetic resonance imaging (fMRI) is an anatomical imaging method which uses magnetic fields in order of 1–2 Tesla to create accurate images of the hemodynamics of the brain. Magnetoencephalography, (MEG), in contrast, is a technique where magnetic fields created by spontaneous brain activity in order of few picoteslas outside the head are measured and used to create an accurate image of brain activity.

Since both of the aforementioned techniques use either extremely strong or weak magnetic fields for imaging purposes, it is not possible to use regular electrodynamic headphones for auditory stimulation. In this research, a tubephone system was constructed. The system consists of a digital signal processor (DSP), power amplifier, special electrodynamic loudspeakers, adapter horns, and a tube system. The poor frequency response of the tube system was equalized with inverse filtering performed with the DSP.

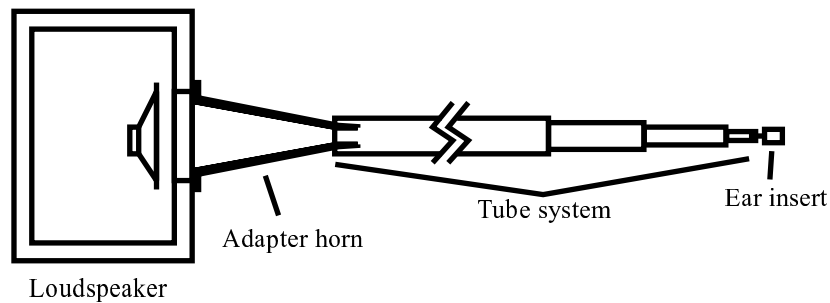


Figure 1: A diagram of the tubeophone system construction.

2. SYSTEM OVERVIEW

The physical design consists of the loudspeakers, adapter horns, tube system and the ear pieces (see figure 1). The loudspeakers are of single element design and two liters of volume. The element used was Audax AT080M0. During the design process of the system it was noted that it is beneficial to attach the transducer element inside of the loudspeaker box to create an acoustic leak so that there is a 2 cm gap between the element and the box. This was done to suppress the strong low-frequency resonance at 200–700 Hz.

The loudspeakers are connected to the tubes by adapter horns. The horns were lathed from PVC plastic to a cone shape. The adapter horns were attached tightly to the loudspeakers in front of the transducer element. The tubes were attached to the adapter horns by means of a friction joint.

The tube system consists of flexible plastic tubes. Major portion of the tube is made of PVC plastic. A large tube diameter attenuated high frequencies less than a thin tube, but was also stiffer and more cumbersome to use. Softer tube materials would increase the flexibility of the tube, but also the high frequency attenuation of the system. Additional restrictions to the tube diameter were imposed by the sizes of measurement room wall openings. Tube inner diameter of 2–2.5 cm appeared to be most practical in use.

The large diameter main tube has to be narrowed down to fit the eartips, which have tubes of 1.6 mm of inner diameter. In this experiment a piecewise change of diameter was used. The transition was done by connecting different diameter tubes with suitable friction joints. Finally, it was noted that the last 20–50 cm, depending on the installation environment, has to be flexible and of relatively thin tube to increase comfort and ease of use of the tubephones.

For simplicity, the ear pieces used in this experiment were standard EARLINK 3A ear inserts.

3. EQUALIZATION

In figure 2 (a) the uncorrected frequency response of the tube system is shown. Depending on the tube and loudspeaker construction, the maximum equalization needed is 30–50 dB. Above that, different distortion and dynamics problems become too severe for good quality

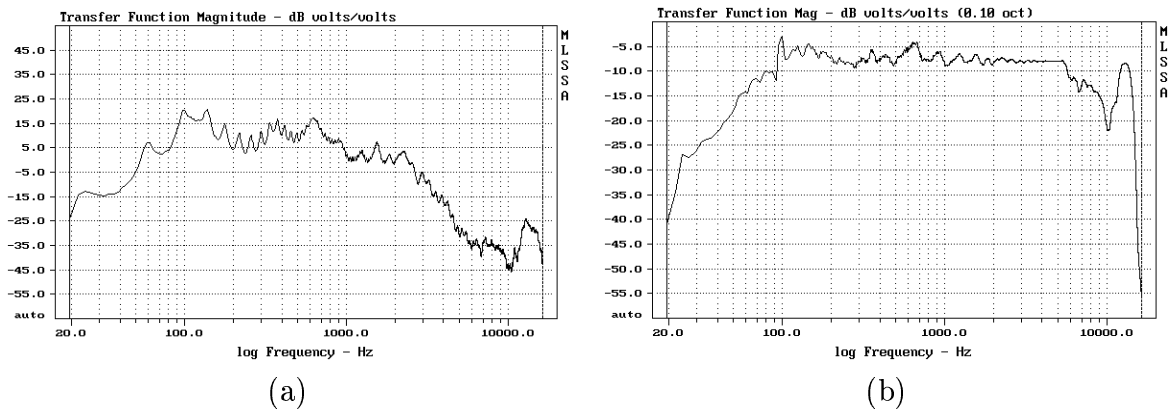


Figure 2: Unequalized (a) and equalized (b) frequency responses of the tube system. Notice the scaling.

audio reproduction.

The equalization was performed with a fixed point DSP system using 256-tap FIR filter, which in the later systems was complemented with an echo cancellation filter consisting of a delay line and another 256-tap FIR filter. Other filter types such as regular and warped IIR filters were also considered [1].

The tube impulse responses were measured using MLSSA maximal length sequence impulse response measurement system. The measurement microphone used was Brüel & Kjær Type 4157 occluded-ear simulator [2].

The equalization filter design was performed as follows. The inverse of the magnitude response was calculated, and then conditioned it by band-limiting the response and flattening the strongest resonance peaks. Then the inverse filter was designed to match the conditioned inverse of the magnitude response. The maximum amplification of the filter was set to 45 dB.

The echo cancellation system was designed to suppress the first echo after the main impulse. The level of the unwanted echo was only 20–30 dB below the main signal level, and in some cases it was audible and disturbing. The cancellation was performed by first fitting a delay line of suitable length after the main equalization filter so that the echo cancellation filter was at the position of the first echo. The echo cancellation filter was then designed to nullify it from the response. The resulting frequency response is shown in figure 2 (b).

4. EFFECTS OF DISTORTION

The intermodulation distortion of the loudspeaker element was a constraint for the maximum amount of an equalization. It was noted, that typical elements induce distortion at the difference frequency of two signal components. For example, if there is a signal that is a sum of two sine waves, $f_1 = 5 \text{ kHz}$, $f_2 = 5.5 \text{ kHz}$, both having a relative amplitude of 0 dB, a distortion component at $f_{im} = 500 \text{ Hz}$ is induced. The distortion has typically an amplitude of -40 dB below the main signal components.

Since the loudspeaker elements are equalized with a strong hi-frequency amplification, the distortion in some cases produced very unpleasant audible low-frequency artifacts. Typical

natural sounds with decreasing high-frequency spectral energy somewhat counteract the distortion phenomenon, but it has to be noted especially when performing auditory experiments with the system.

5. APPLICATIONS

The tubeophone system is intended to provide wideband audio playback capabilities to spaces where regular equipment can not be used because of the magnetic interference problems. These include fMRI and MEG measurement systems.

Ability to perform brain research using wideband auditory signals was the main motivation behind this research. For that reason, sound quality was initially the main design criteria. It was soon noted however, that the system can be easily used for communicating with, or entertaining the patients during the measurements. In such a secondary use, the patient comfort and ease of use are imperative design criteria. That suggests using thin and flexible tubes, which on the other hand deteriorate the high-frequency response.

6. COMPARISON WITH OTHER CONSTRUCTIONS

In MEG systems it is possible to use ISO 389-2 standard EARTONE 3A or Etymotic ER-3A audiometric insert earphones with extended sound tube which results in a 4 kHz upper limit to the frequency response [3]. While commercially available, these earphones do not provide sufficiently good frequency response for wideband auditory measurements needed e.g. in binaural hearing studies.

In fMRI systems use of electrostatic headphones might be possible. However, they do not permit use of ear mufflers, which are required to suppress the high-level operating noise of the fMRI system.

7. CONCLUSIONS

This research has shown that with proper combination of acoustical design and use of DSP it is possible to create a tubeophone system which has wideband audio reproduction capabilities allowing studies with binaural and natural signals.

Four such tubeophone systems have been built and are in operation in different hospitals and research laboratories around Finland. These systems have shown that the tubephones are a practical and useful tool in brain research.

8. REFERENCES

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