DESIGN AND VALIDATION OF A BONE CONDUCTION MUSIC PLAYBACK FOR BIKE HELMET

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Abstract

This paper presents a proof of concept to develop a system of bone transducers that would equip a bike helmet and provide music directly to the cochlea by bone conduction. The purpose of this design is to allow the ears of the wearer to remain unobstructed to ensure a comfortable music listening while maintaining auditory awareness and localisation capabilities. A review of the scientific literature about bone conduction shows that of all possible skull locations, the condyle of the jaw presents the lowest threshold level of auditory perception when excited. This determined the choice for the final mounting system and the process for the audiometric measurements. The main result is a digital filter obtained with the output magnitude of the transducers and designed to provide comfortable and unobstructed music listening.

Keywords: Product design, bone conduction, sound reproduction, vibrator, consumer product, hearing threshold

Résumé

Cet article présente une preuve de concept liée au développement d'un nouveau produit, un système d'ostéovibrateurs équipés sur un casque de vélo permettant de fournir directement une écoute musicale à la cochlée par conduction osseuse. L'objectif de ce design de produit est d'obtenir une écoute musicale confortable et sécuritaire en maintenant les oreilles de l'utilisateur non-obstruées et en garantissant que ses capacités de vigilance et de localisation auditives restent intactes. Une revue de la littérature scientifique et technique au sujet de la conduction osseuse montre que parmi toutes les localisations crâniennes possibles, les condyles au niveau du haut des mâchoires possèdent le plus bas seuil de perception auditive lors-qu'excités. Cela détermine le choix de système de fixation et la procédure à suivre pour les mesures audiométriques. Le résultat principal est un filtre obtenu en mesurant l'amplitude en sortie des transducteurs et conçu pour fournir une écoute musicale confortable et sécuritaire.

Mots-clés: Design de produit, conduction osseuse, reproduction sonore, vibrateurs, produit de consommation, seuils auditifs

1 Introduction

Accidents involving people wearing headphones while biking are frequent [1]. To resolve this safety issue and still permit bicyclists to listen to music, a music playback device that allows for the external ear to be unobstructed can be designed [2]. Bone conducting headphones are a viable type of system that could resolve this issue [3].

This work aims to ensure comfortable and safe music listening while bicycling. In order to choose the most reliable device to equip a bicycle helmet, research of different types of bone transducers adapted to music listening was required.

One aspect of the product design consisted in characterizing the bone transducers in terms of frequency response. The objective of this modeling is to see if the filter obtained could be used for the equalization of the sound emitted by the transducers.

Another aspect of particular interest is the skull behavior for this kind of excitation in the context of finding the ideal location where to affix the bone transducers within the helmet.

Issues that will be addressed in this study:

- How will the bone transducers be attached to the bicycle helmet once the ideal bone conduction location on the skull has been identified?
- How to bypass the fact that the instrumentation used for the measurements will probably not be calibrated for the studied bone transducers?
- Will the filter obtained after the measures be usable for the equalization of the sound emitted by the transducers?

After enunciating the main issue, the bibliographic studies pertaining to bone conduction will now be reviewed. Research includes documents dealing with the vibro-acoustic sensitivities of the skull and with the concept of headphones using a bone transducer.

This article begins with a background summary of the theory causing the bone conduction then the methodology and methods implemented during the feasibility study. This feasibility study determines on the one hand if the desired osteo-vibratory level is accessible by verifying those generated by different types of bone transducers. On the other hand the modeling of the selected bone transducers shows their characteristics such as the input voltage required and the vibratory output pressure applied on the skull together with the intracranial frequency response. This step is crucial for

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choosing the most appropriate location to place the bone transducers before subsequent measurements are taken.

In the concluding section this article presents the project results and an analysis dealing with the interpretation of these results and the validation of the concept.

2 Background

Bone conduction is a phenomenon in which sound propagates from an extra-cranial point to the cochlea through the skull.

Bone conduction is one of the reasons why someone's voice seems different for him or her when it is recorded and reproduced. Because the sound leaving the vocal chords (especially low frequencies) is also transmitted via skull bones to the inner ear, people perceive their own voice lower and deeper than others.

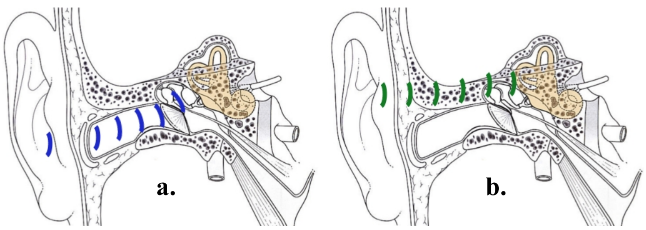


Figure 1: Air vs. bone conduction (adapted from Descouens [9])

The sound propagation of classical headphones (Figure 1.a.) is created by the vibrations of the molecules in the air and these vibrations are collected and concentrated by the pinna, which is the visible part of the ear. The waves then follow the ear canal and create vibrations in the eardrum. The middle ear ossicles amplify the signal and deliver it to the cochlea whose role is to analyse the sound wave before transmitting the relative information to the brain.

In the case of bone conduction headphones (Figure 1.b.), bone conduction transducers are placed onto the skull. The waves then propagate from the skull bones to the cochlea, which processes the sound signal.

Thus the major difference between bone conduction and the traditional headphone system is that the music and ambient sounds do not follow the same path. With bone conduction it is possible for the inner ear to perceive both sound sources almost simultaneously:

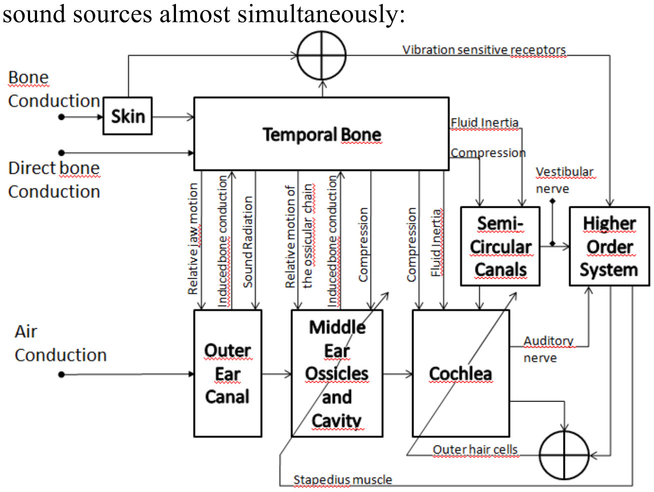
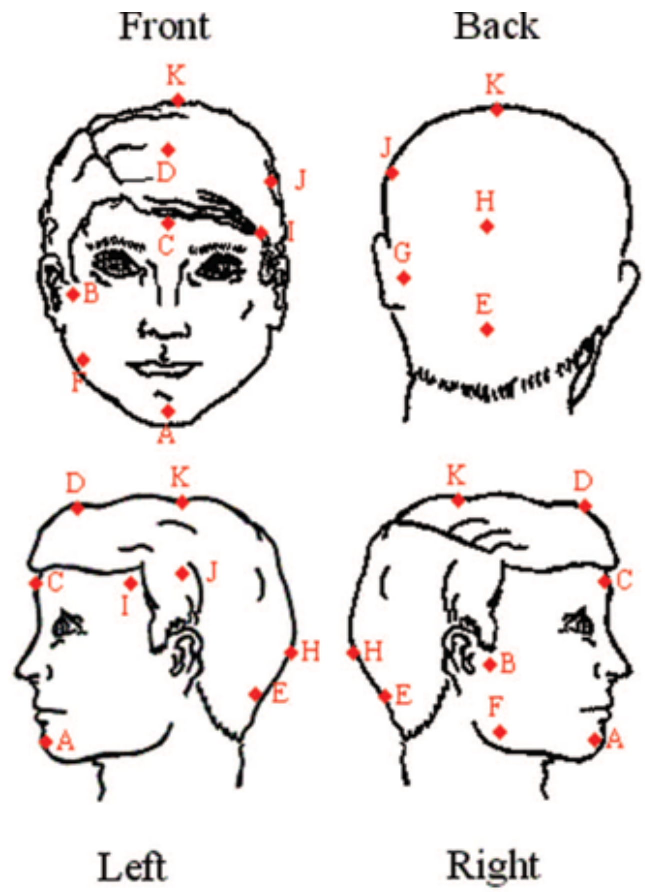


Figure 2: Modeling of the sound paths including bone and air conduction (adapted from Stenfelt [5])

3 Materials & Methods

3.1 Human skull susceptibility to vibrations

Past studies have demonstrated that the human skull has different frequency responses depending on where the vibratory force is applied [6] [7]. To see where this frequency response is the least attenuated, it was necessary to compare the values of threshold levels in the results of these studies for each application point. The cartography showing these different application points is displayed in Figure 3:



Key

A	Chin
B	Condyle
C	FPz
D	Fz
E	Inion
F	Jaw Angle
G	Mastoid
H	Pz
I	Temple
J	T3
K	Vertex

Figure 3: Cartography of application points studied on a human skull (adapted from McBride [6])

Four of these application points were selected and compared:

- The condyle (B)
- The mastoid (G)
- The temple (I)
- The vertex (K)

These four application points present the lowest threshold levels according to the two consulted studies. The jaw angle (location F) point also has a suitable threshold level but as it is located in the lower jaw as chin (location A) point, it is subject to a greater standard deviation than the other locations and was not retained because of the unpredictable micro-deviations of the temporomandibular joint.

These results are crucial for knowing exactly where the mounting system for the transducers is to be placed on the bicycle helmet, so that it also stays in contact with the condyles.

3.2 Measurement of the auditory thresholds with the proposed transducers

After the bone transducer was selected, measurements of the auditory hearing thresholds were taken for 23 third octave band frequencies on fifteen normal hearing subjects aged 25 years on average (age range : 20 to 33 years of age). These subjects were self-reported as not suffering from any hearing impairments and can be therefore considered representative of the typical end-user of the developed technology. Yet the measurements were performed with a functional prototype of headphones staging the bone transducers exciting the condyles. The equipment used includes an audiometric booth (ECKEL Model C-27 S) and a clinical audiometer (Interacoustics Model AC 40).

As the audiometer used was calibrated for a clinical audiometric bone vibrator very different from the one used in this study, the hearing levels values acquired by the audiometer in dB HL could not be used directly nor could be adjusted for the proposed transducer, as such calibration curve did not yet exist. Instead, a more straightforward direct voltage measurement was performed as detailed in Section 3.3.

3.3 Measurement of the bone transducers frequency response

As the hearing thresholds were established using the proposed transducer for normal hearing test-subjects, it was assumed that the average response would correspond to a 0 dB HL level. It was then possible to measure with a true-RMS multimeter (AMPROBE Model 34XR-A) connected to the bone transducers, the RMS voltage that was generated by the audiometer when generating that average 0 dB HL stimuli across all third octave-band center frequencies. These voltage values could then be paired with the values of the auditory threshold levels measured earlier in order to assess the proposed bone transducer frequency response.

3.4 Design of an equalizing filter

To equalize the output level of the transducers following the frequency response established previously, a digital filter was set using the magnitude of the input voltage curve established in Section 3.3. The coefficients of the impulse response of the digital filter are obtained using a filter design and identification toolbox available within MATLAB computing software.

4 Results

4.1 Bone conducting hearing thresholds as a function of the application points

Human skull behaviour for the four chosen application points is illustrated on Figure 4 for each octave frequency band from 125 Hz to 8 kHz. The values were extracted from tables in the results sections of the previous cited articles [6] [7]:

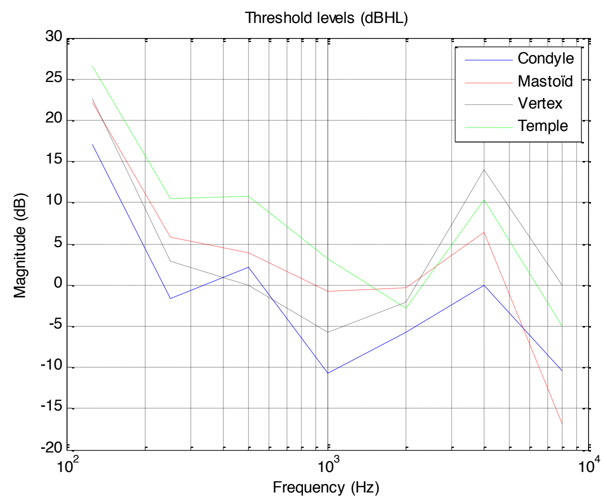


Figure 4: Hearing threshold levels at different locations on the human skull

Using these curves, it is possible to rank the application points from the lowest to the highest threshold level in order to find the most sensitive location for the bone transducers placement:

Table 1: Relative sensitivity of the chosen application points

F (Hz)	[125 ; 500]	[500 ; 2k]	[2k ; 8k]
Condyle	#1	#1	#1
Mastoid	#3	#3	#2
Vertex	#2	#2	#4
Temple	#4	#4	#3

4.2 Mechanical modeling of the proposed transducers and its fastening system

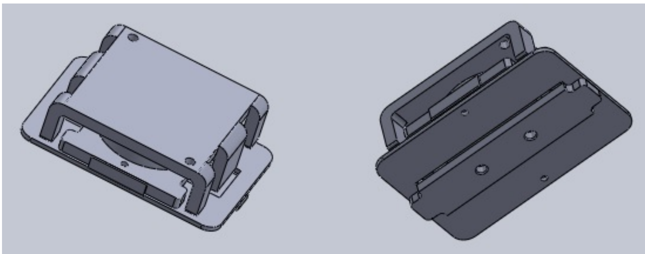


Figure 5: Bone transducers selected for the proposed application

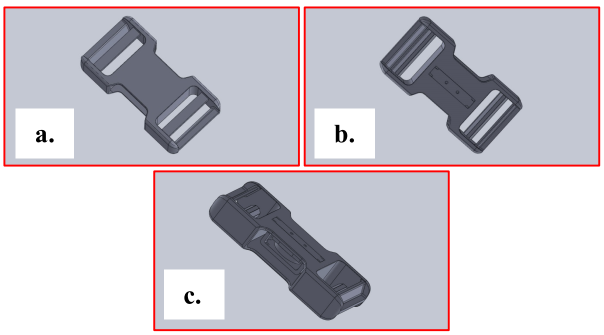


Figure 6: 3D model of the proposed fastening system a) back, b) front, c) sideways

The fastening system proposed for encapsulating the bone transducers modeled in Figure 5 is shown in Figure 6. The shape of this fastening system has been adapted to fit with the bicycle helmet straps. So it can be adjusted along the straps to ensure the contact with the condyles of any user.

4.3 Experimental validation of the proposed transducers design

Hearing threshold levels:

Figure 7 is an illustration of the result of the subjective measures of hearing threshold levels that were measured on fifteen normal hearing subjects. These measures were performed on each condyle for each third-octave band frequency from 125 Hz to 8 kHz:

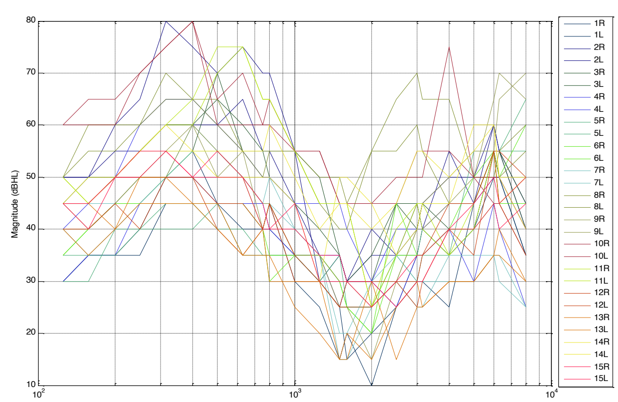


Figure 7: Individual audiometric levels measured on the 15 normal hearing subjects

The group average response curve presented in Figure 8 is an intermediate result that will be used to access the "zero" for the calibration of each bone transducer on the audiometric equipment. It is also a way to verify that the left and right bone transducers do indeed have the same frequency response:

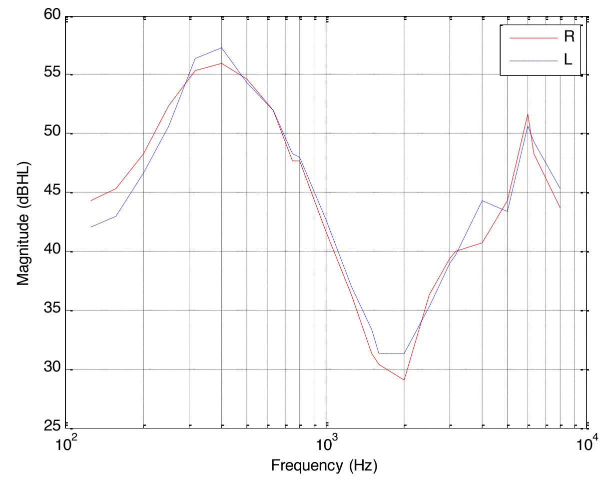


Figure 8: Audiometric levels – Left transducer in blue and right transducer in red

Average audiometric threshold levels for the left and right transducers are shown on Figure 9 as well as the statistical standard deviation of the hearing threshold measurements per third-octave band frequencies on the group subjects:

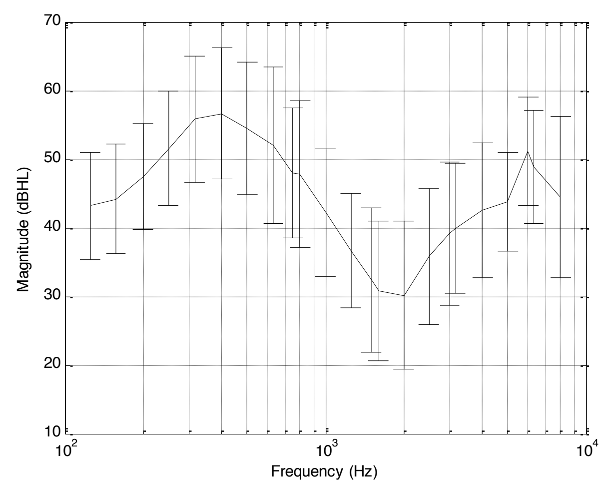


Figure 9: Audiometric threshold levels – Group mean and standard deviation per third-octave band frequencies

Input voltage:

The left and right input voltage of the bone transducers when generating a "flat" uniform stimulation are shown on Figure 10, reusing the response curves obtained in Figure 8:

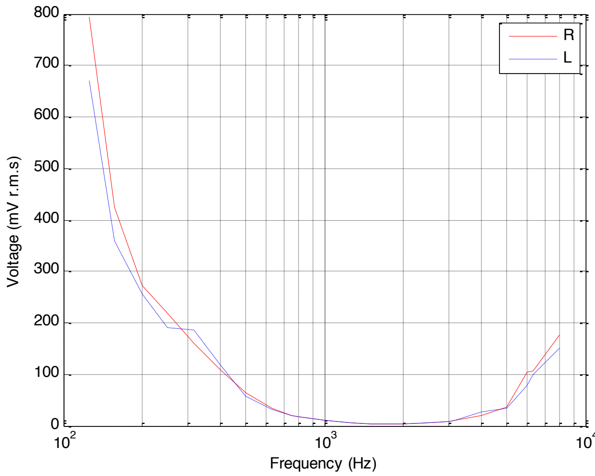


Figure 10: Bone transducers input voltage for a "flat" uniform bone stimulation – Left transducer in blue and right transducer in red

As can be seen on Figure 10, to generate a "flat" uniform stimulation much more electrical power is needed in the low-frequencies than in the medium frequencies because of the low efficiency of the transducers in low frequencies.

The magnitude of these values at each third-octave band frequency represents the frequency response of the transducers and can be used to design a filter model.

Design of an equalizing digital filter:

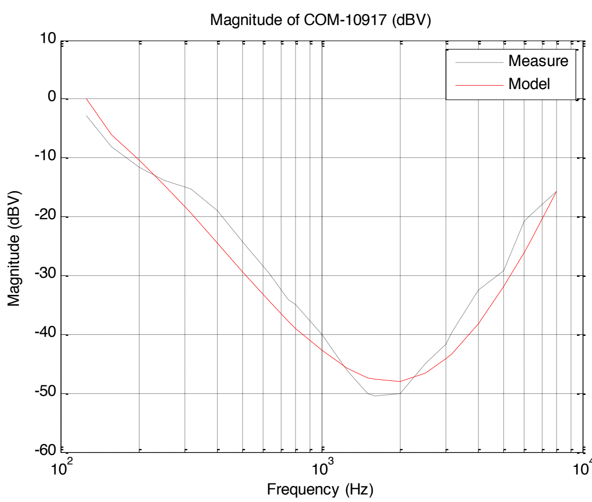


Figure 11: Magnitude of the bone transducers frequency response (in black) and of the fitted digital filter (in red)

The magnitude of the average response from Figure 9 and of a corresponding theoretical transfer function modeled under MATLAB Filter Design Toolbox is illustrated on Figure 11.

This model is an order 3 notch filter defined with two cut-off frequencies:

- A low cut-off frequency of 125 Hz.
- A band frequency equal to 2.4 kHz.

With the defined model, it is possible to calculate the coefficients of a digital filter and plot its impulse frequency response. The coefficients were calculated with a reverse Z-transform starting from the equation of the model curve (red line in Figure 11). This equation is the reason for creating a model before calculating the coefficients, because it is not possible to obtain the filter directly with the results of the measures.

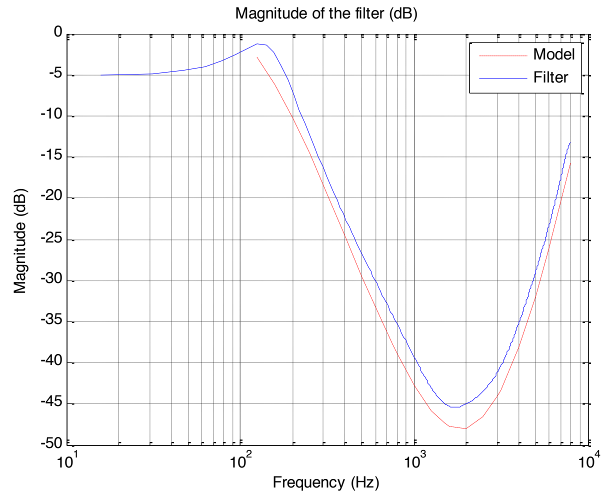


Figure 12: Frequency response of the filter (in blue)

Validation of the filter:

To verify that the digital filter actually improves the quality of the sound signal, a subjective comparison was conducted using an excerpt of a test song. First, the excerpt was played non-filtered, then filtered. The criteria of comparison included the relative sound level, restitution of low, medium and high frequencies and comprehension of the lyrics.

The comparison between the not filtered and the filtered song excerpts has shown that the sound quality was often preferred when the signal was not filtered. Indeed, it appears that the equalization that was conducted at threshold levels do not correspond to an equal loudness perception at higher levels.

For illustration, the ear is less sensitive to low-frequencies at low level, but this sensitivity increases as the level of the music playback increases. As a consequence, an equalizing filter that would flatten the response at 0 dB HL would sound way too “boomy” when listened to at higher levels.

Since this higher level playback of the music is highly variable among individuals, it is not possible to fix the loudness correction that is to be applied to the equalizing filter. To address that issue, one last development was conducted, where the user can adjust the loudness correction manually using the graphical equalizer illustrated in Figure 13.

This graphical equalizer is equipped with a popup menu containing the settings relative to most of the musical styles and also with a custom mode allowing users to adjust by himself or herself the preferred playback sound level. In doing so, simply manipulate the sliders representing each frequency (displayed here per octave bands from 31.25 Hz to 16 kHz) in order to modify the corresponding sound level by providing it a variation between -12 and +12 dB.

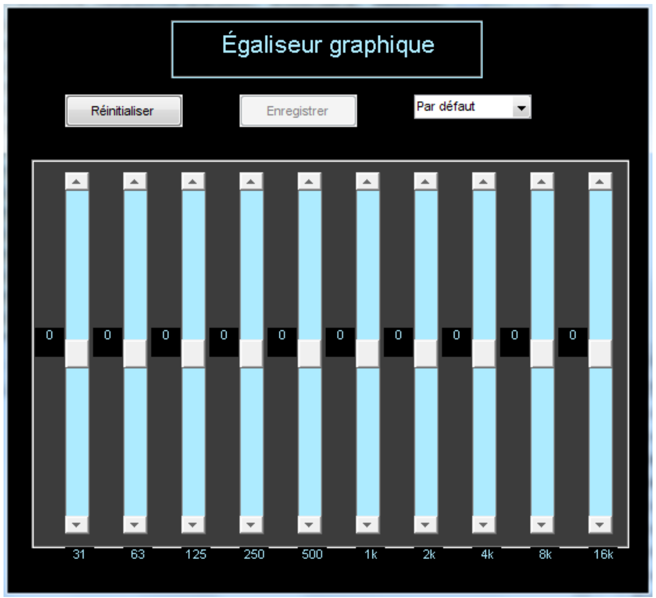


Figure 13: Graphical equalizer interface for the required loudness correction

5 Analysis and Discussion

The proposed mounting system displayed in Figure 6 stages a simple way to encapsulate the bone transducers. The system can be glided along the front helmet webbing, which proves a simple way of adjusting its position against the skull. Another benefit of the proposed design is that it can be retrofitted on any existing helmet.

The standard deviation of the curves displayed in Figure 7 and which is shown on Figure 9 may appear to be large but was not felt to be a concern as the aim of the audiometric measurements was to obtain the general shape of the equalizing filter, knowing that individuals may indeed have a different hearing sensitivity that would be anyway later on adjusted through the loudness correction mechanism described in Section 4.d.

Finally, one can foresee that the loudness correction required on top of the equalization filter could be implemented on a portable music player as most of these devices now support "apps". It would even be feasible to have the app adjusting automatically the loudness correction as a function of the actual music playback level, as the frequency response of the proposed transducer has been properly identified and that loudness correction models are easily programmable in modern digital signal processors.

6 Conclusions

This project's objective was to develop a system of bone transducers that would equip a bike helmet and able to excite the skull via bone conduction. This technological development would ensure comfortable music listening, while enabling the ears to remain unobstructed so that the wearer may retain awareness and localisation capabilities.

The main result of this project is a functional bicycle helmet prototype validated in laboratory staging two components mounted onto the helmet straps and containing the bone transducers.

Future research needs are to validate the proposed bike helmet prototype on a larger number of test-subjects, as inter-individual differences in perceived audio quality can be significant [8]. Future developments should be conducted to encode the equalization filter as well as the loudness correction into an "app" that could be running on the portable music player. Wired connections could be also replaced with wireless link such as a Bluetooth protocol, as more and more cell-phones and music players feature that music streaming capability.

Figure 14: Final prototype

Acknowledgments

The first author would like to thank the members and researchers of ÉTS industrial acoustic laboratories for their continuous support during his engineering internship.

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