AURES, a binaural in-situ probe measuring system

Development of a practical hardware solution as well as a suitable algorithm, software-based, for the associated volume, loudness.

The aurally compensated measuring and calculating of the subjective perception to the transfer function of car audio systems still presents exciting challenges. During my work in the development of audiological measurement technology (hearing aid acoustics), my interest in the front of sound reinforcement technology, especially for the automotive sector, is still alive. The development described below, of making ambitious car hi-fi enthusiasts or installers accessible, instead to a vehicle or measuring instrument manufacturer, is appealing from this point of view. The search for a suitable partner, an innovative car audio manufacturer, was not difficult.

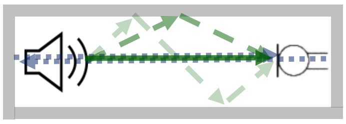
Prolog, first some basics as an orientation for the following description.

<u>Open field</u>

In the open field, the acoustic transmission between a sound transmitter, for example a loudspeaker, and a sound receiver, for example a microphone, is only affected by the attenuation of the air.

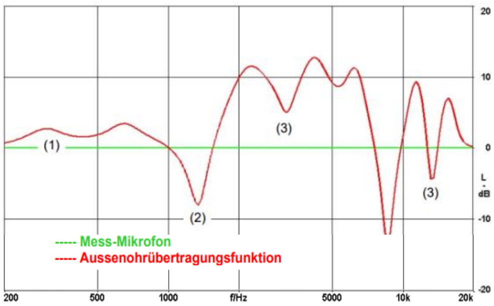
<u>Room acoustics</u>

In a closed room, the influence of reflected sound, modes (resonances) and the pressure chamber effect is added.

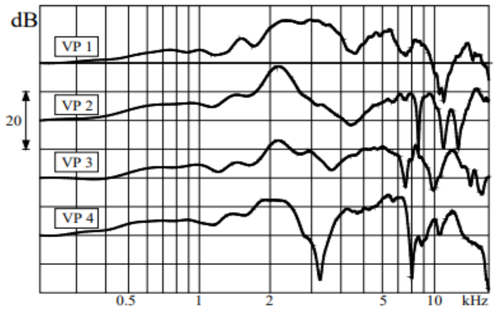


<u>Psychoacoustics</u>

If the sound receiver is a person's hearing instead of a microphone, the sound field is also distorted by the person's own head and torso. However, since these distortions(*) are constantly present, the brain, mathematically simplified comparable to a correction value or over the entire auditory range of a correction curve (outer ear transfer function), deducts them from natural perception or does not consciously hear them as unnatural or faulty frequency response.



* Definition distortion ≈ frequency-dependent influence of the frequency response and the time offset, not distortion factor



Some typical outer ear transfer functions measured on four subjects for the 0° forward direction

<u>Individual hearing</u>

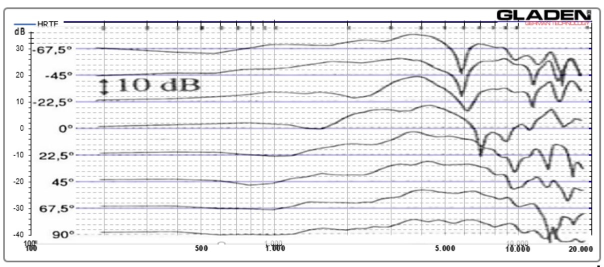
The anatomy makes a distinction between different people, so the correction curve (outer ear transfer function) for acoustic perception varies from person to person.

<u>Spatial hearing</u>

The fact that the human ear has two ears and thus enables directional hearing left/right is not enough to further derive the ability to make a distinction between top and bottom and back and front (three-dimensional hearing).

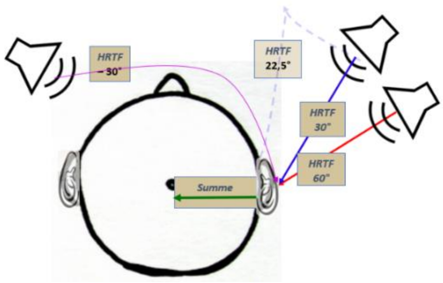
<u>HRTF</u>

Due to the acoustic influence of the auricle, head and torso (upper body), the sound reaches the eardrum in different distortions depending on the direction of incidence (as well as time). The brain uses these differences for localization. Scientifically, the direction-dependent influence is called HRTF "Head-Related Transfer Function".



Auditory canal & eardrum

Illustration HRTF example ear from -67,5° to +90° in horizontal plane.



Simplified example graphic horizontal, one ear, 3 speakers, 1 reflection

No matter from which direction sounds hit the ear and how they were distorted by the HRTF depending on the direction, they reunite in the auditory canal to form a one-dimensional sound path. There is no separate signal flow to different directional sounds (front rear, top bottom). In the ear canal and the following eardrum all sounds are again given in a sum signal.

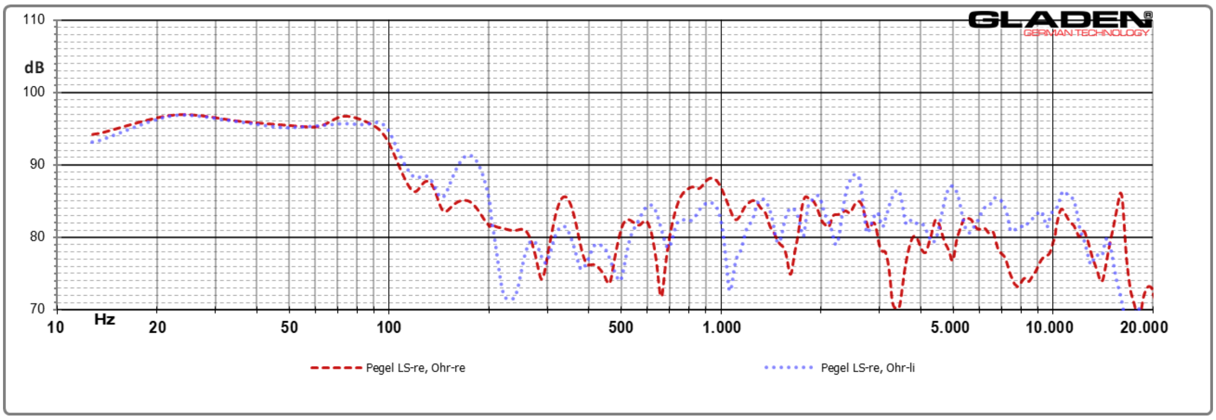
Therefore, only the two signals from the left and right ear are available to the brain for evaluation as acoustic stimuli (except for low frequencies < 100 Hz concerning structure-borne sound). In addition to the influence of direction-dependent distortions of the frequency response on the sum signal (ILD), it also evaluates time differences (ITD).

Music reproduction in car cabins

The car cabin is a small room. When reproducing music via loudspeakers, there are interactions between the close boundary surfaces of the interior and the head and torso of the listener (mode/resonance, shadowing). For high-quality reproduction characteristics, the aim is to measure and correct these influences with the correct hearing. Previously common measuring methods, with the exception of the dummy head, are not suitable in principle to measure the reproduction characteristics with sufficient precision. The following graphics show the influence of shading and modes / resonances by head and torso as well as differences of common measurement methods to an HRTF corrected measurement in the auditory canal.

Influence of head and torso

The off-centre seating position of the passengers, resulting in a considerably asymmetrical arrangement of the loudspeakers of a stereo system to the passenger, with sometimes resulting high false angles, often distorts the transmission behaviour to the eardrums of the passenger by its own head and torso, depending on frequency, by well over 10 dB. The following graphic shows the frequency response of a right speaker system on the right and left ear. Below 1600 Hz, the level on the left ear is usually lower than on the right ear due to the shadowing of the head. Above 3000 Hz, however, due to window reflections and mode formation between window and head side, the level at the left ear facing away from the loudspeaker is largely higher, frequency-dependently up to over 10 dB, than that at the right ear facing the loudspeaker.

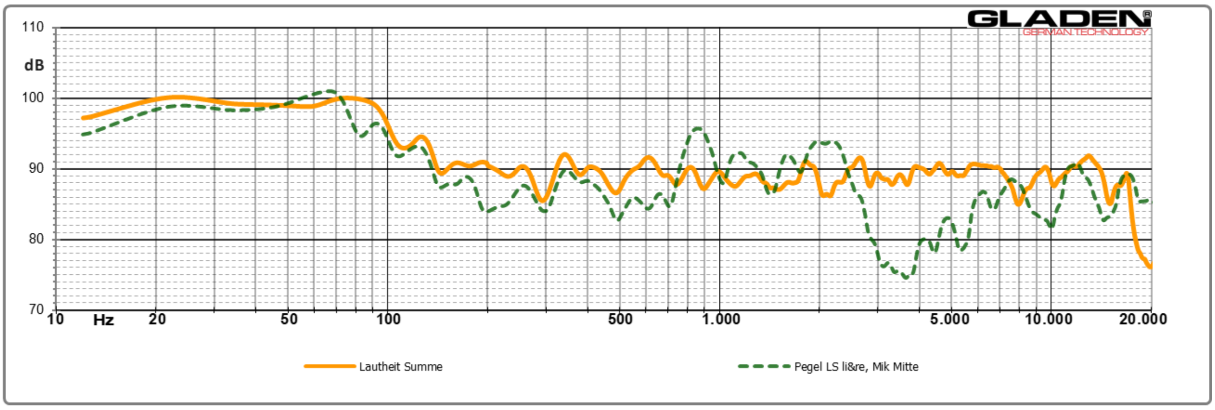


Binaural hearing

People always hear with both ears (binaural). In the brain, even if the signals in the right and left ear differ considerably, subjectively there is always an auditory event. It is not possible for the awareness to hear sound separated from the left and right ear. The fact that this is not self-evident is shown by the comparison to seeing, during squinting two separate (partly overlapping) images are perceived. In the following comparison measurements this is taken into account in the yellow curve, it shows the sum signal from the left and right ear including HRTF correction.

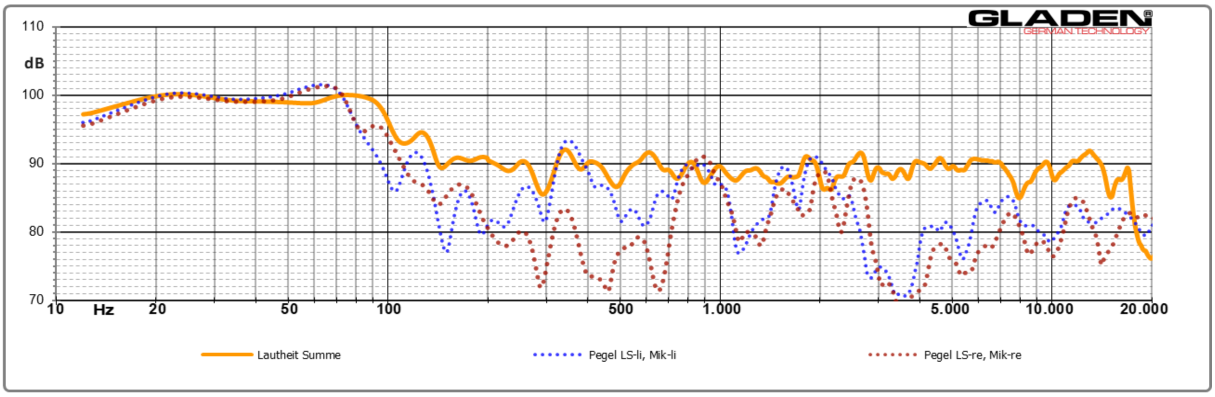
Acoustic measurement without head & torso

The yellow curve of the following graphic shows the resulting frequency response of a monaural signal (left and right coherent, common reproduction). The green curve shows the measurement of a microphone positioned approx. 15 cm in the middle in front of the headrest.

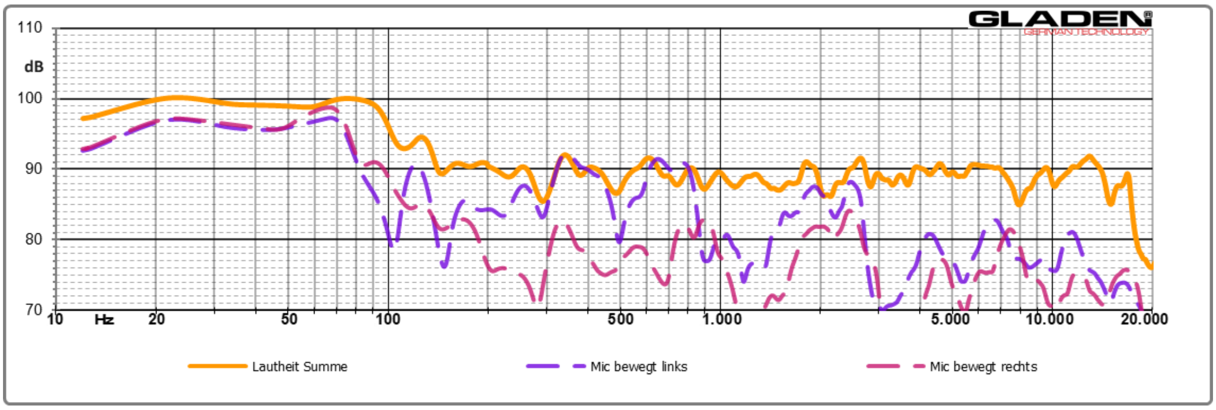


Acoustic measurement with head and torso, outside the head

Here the influence of head and torso is included in the measurement, but there is no measurement point outside the head that corresponds to the frequency response in the auditory canal or at the eardrum. For example, the influence of the auricle (Pinna) on the sound at a point in front of the auricle, depending on the direction of incidence, does not yet exist. In order to record these in a correction curve, the measuring system would have to know from which direction the direct sound and each of the countless reflections comes. The graphic shows the comparison between binaural auditory canal measurement (yellow) and one head end measurement each with approx. 5 cm lateral headroom of the microphone. In accordance with common measurement practice, only the loudspeaker system on the measuring side was switched on (left loudspeaker system to microphone on the left side of the head, right loudspeaker system to microphone on the right side of the head).



The following graphic shows the comparison of the binaural auditory canal measurement (yellow), another common measurement procedure, the measurement with moving microphone (waggle method ->microphone moves from left to right during measurement), blue left, red right head side. Both speaker systems (left and right) were activated for the measurements (common monaural reproduction).



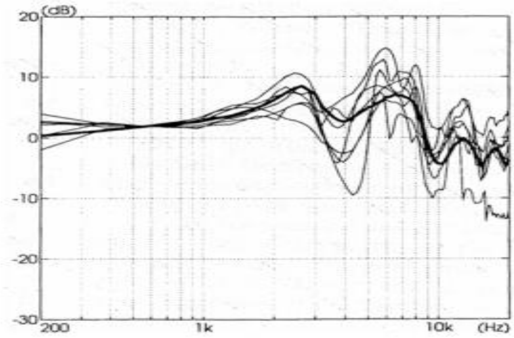
Calculation of a mathematically derived HRTF correction

The interior of the vehicle consists of numerous absorbent and reflective boundary surfaces. At least there are one left and one right loudspeaker system as sound transmitter, and one left and right ear as sound receiver, each with frequency- and three-dimensional direction-dependent characteristics. This in connection with the further calculation of a virtual head/torsos is complex, even with complex FEM calculation, independent of the number of available transducers (microphone arrays) is not sufficient so far. Noise-canceling headphones give an indication of restriction. Although simpler conditions than car audio systems, actively controlled, these only reduce the lower frequency range. In the midrange and high frequency range, the given noise reduction is achieved as purely passive hearing protection.

As a logical consequence of the defectiveness, no measuring method without head/torso or outside the head has been established for motor vehicle cabins to date.

Dummy head measurement

When measuring with a dummy head, many imponderables for measuring without or outside a head are eliminated as a matter of principle. Coherent to natural hearing, the signal is measured here, including all perceived influences by air, space, HRTF. However, replicating the anatomy of a real head is not trivial. An indication of this can be seen in differing diffuse field frequencies of the artificial heads of different suppliers. (Graphic taken from "A Communication from the Standards Committee for Psychoacoustic Measurement Technology, H. Fastl 2007). This leaves a considerable scope for variation as uncertainty.



Localization by head movement

Both the sound characteristics heard as well as the localization ability are influenced by constant, mostly not consciously executed, head movement. These changes via the dummy head to the measurement is complex for the production of the same as also in the application. For example, the simulation of the surface change between torso and head during head rotation. The relevance of this consideration can be seen when looking at headphone playback. When the head moves, the playback parameters do not change here. As a result, no matter which frequency response is given / which frequency response correction took place, mostly for localization in the head.

With this system we comfortably solve all challenges discussed so far!

Hardware

- The primary hardware of the BIM consists of two measuring probes that a natural person (as part of the measuring equipment) such as in-ears or hearing systems inserts directly into the ear canal (Insitu, lat. ≈ to the location of the event). An important feature here is that after each removal, the sound pickups return to the same position in the auditory canal with millimeter accuracy when inserted again. This is due to the shape of the complete unit, which fits almost snugly into the anatomy of the ear. Measurement tolerances due to differing positioning are minimized and reproducible measurement results up to 20 kHz are possible.

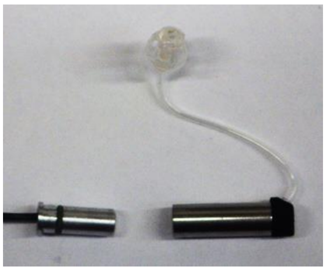
- The probes of the BIM influence the acoustics in the auditory canal less than +- 1 dB on average. The influence of the sound field between the auricle and the ear canal entrance and its influence on the HRTF remains correspondingly low. In the reverse conclusion (simple practical test) there is no noticeable difference in hearing with or without the probe microphones.

  This is possible by placing the actual microphone behind the ear and connecting it via a 0.9 mm thick sound tube in the ear canal. Tricky, shape and volume of the sound opening of the sound tube to the microphone are designed so that tube resonances are effectively attenuated when used in the auditory canal. The back pressure of the ear canal, tube length and diameter as well as the coupling volume in front of the microphone capsule form an acoustic unit.

  The sound tube end in the ear canal, the sound tube opening, is provided with a thin silicone guide, which guides the tube end approx. centrally in the ear canal, thus preventing the transmission of structure-borne sound from the edge of the ear canal to the sound tube. The end piece also has the task of keeping the sound tube sufficiently stable in the ear canal so that it does not change its position during head movements or even slip out.

- For very small or large auditory canals, both the sound tube and the end pieces are available in three different sizes. They can be easily changed without tools if required.

- The probe unit can also be disassembled into two parts. After opening the bayonet fitting and removing the sleeve with sound tube, a high-quality measuring microphone is obtained. It serves as a calibration basis. No further reference measuring microphone is required to create the characteristic of an individual outer ear transfer function as a basis for the measurements.



- A suitable holder for the reference microphones has also been thought of to make the measurements for creating the individual characteristic as comfortable as possible.

- The dimensions of the microphone unit behind the ear are 6.5 x 20 mm, so that the HRTF is not significantly affected. The precision required for this miniaturization in parts production and assembly is Made in Germany, the BIM as a whole being an outstanding component of a high-precision measuring process.

- Vehicle or stationary. Carrying the probe unit does not restrict driving ability, thus enabling convenient measurement and creation of corrections suitable for driving operation..

Acoustic properties

- Only one correction curve is required for an individual ear, as all other directional HRTF differences, as actually given, are automatically measured 1:1 in the auditory canal.

- The measurement is carried out with a real person. Due to the principle, no further error-prone correction is necessary, as is the case with a technical replacement (dummy head).

- Influences of head movement and different sitting positions can be recorded easily and realistically. The high degree of consistency in repeat measurements provides safety and enables practical experience of typical influences on defined position changes (lateral head movement, distance between headrests, etc.).

- The calibration of the BIM takes individual anatomical characteristics into account, thus enabling personalized measurement for any person. For example, a sound system can be personalized to the driver/vehicle owner. Uncertainties regarding the correct correction curve are minimized in comparison to the dummy head, because they are created individually for the respective person or his body.

Psychoacoustic evaluation

- People always hear with both ears. In perception, an auditory event is formed from the sum of the two ear signals. The BIM algorithm calculates, taking into account current scientific knowledge of psychoacoustic perception characteristics, from both probe signals the heard volume = loudness.

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