# Two Modified IEC 60318-4 Ear Simulators for Extended Dynamic Range

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*The international standard IEC 60318-4 specifies an occluded ear simulator, often referred to as a 711-coupler, for testing headphones, earphones, hearing protectors, hearing aids etc. The standard specifies a specific microphone type which limits the dynamic range of the coupler both in the low range and in the high. To overcome these limitations, G.R.A.S. has developed two modified versions of the standard ear simulator: A high-sensitive, low-noise version that extends the lower dynamic range below the threshold of human hearing, and a high-pressure version that extends the upper dynamic limit to 178 dB. Also, a new anthropometric ear canal and pinna is introduced. With these, measurements not possible with the standardized configuration can now be made with confidence.*

**The Standard Ear Simulator**

The IEC 60318-4 ear simulator mimics the transfer impedance of a typical human ear. The transfer impedance is defined as the ratio of the sound pressure at the ear entrance to the sound pressure at the ear drum position.
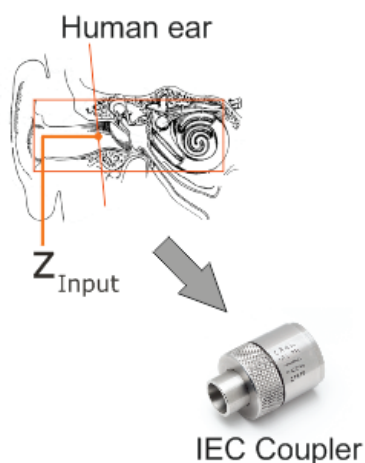


**Fig. 1.** *Ear transfer impedance*

In the simulator the ear drum is replaced by a measurement microphone and the IEC standard specifies that this should be a type WS2P microphone (Working Standard ½" Pressure microphone) as defined in the international standard IEC61094-4. This is a ½" pressure microphone with a sensitivity of 12.5 mV/Pa, and an overall dynamic range from 25 dB(A) (re 20 μPa) to around 160 dB. While this may

be sufficient for many users there are special applications where this is not sufficient, i.e. for measurements of very low levels or very high levels.

For many practical measurements, the 60318-4 ear simulator will be used either as part of a Head and Torso simulator as for example the G.R.A.S. 45BB KEMAR, Fig. 2. This includes two standard IEC 60318-4 simulators, combined with rubber pinnae to simulate the outer ear for testing headphones, hearing aids and similar products.



**Fig. 2.** *45BB Head and Torso simulator*

For testing of in-ear devices like earbuds it may not be necessary to have the full head and torso simulator and the IEC 60318-4 simulator can be incorporated in an Ear and Cheek Simulator like the G.R.A.S. 43AG, Fig. 3.



**Fig. 3.** *43AG Ear and cheek simulator*

**Ear Simulator for Low Level Measurements**
Due to the noise floor of the WS2P microphone in the standard IEC 60318-4 ear simulator, it is not possible to measure levels below approximately 25 dB(A). This is well above the threshold of hearing for the human ear – particularly in the important mid-frequency range where, for instance, most speech energy is concentrated. For precise measurements of electrical and acoustic noise and low level distortion of earphones and active noise cancelation headphones it is necessary to measure at even lower levels.
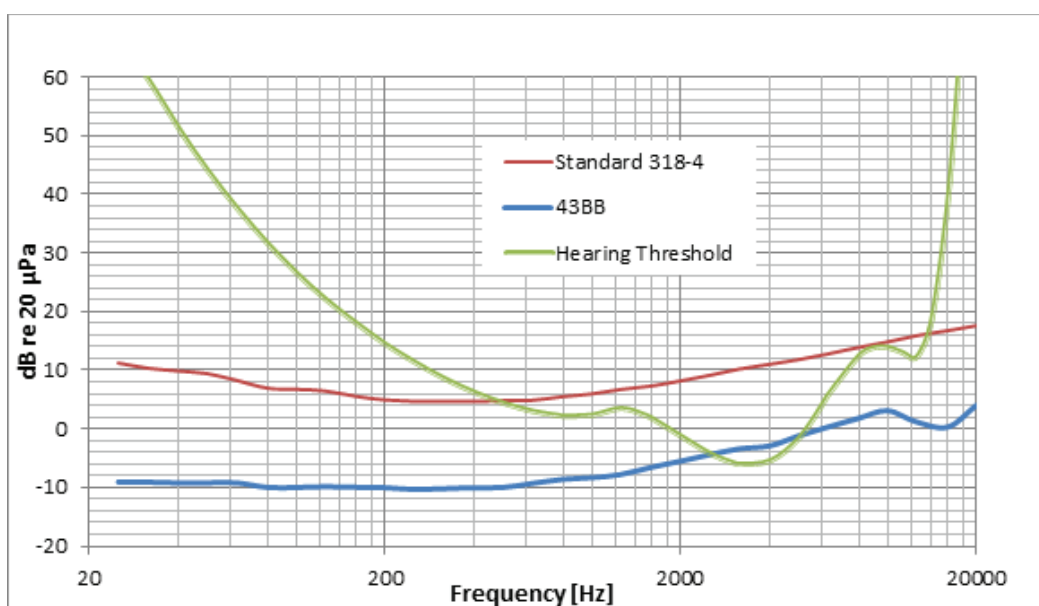


**Fig. 4.** *Linear self-noise of microphones in ear simulators, compared to threshold of human hearing*
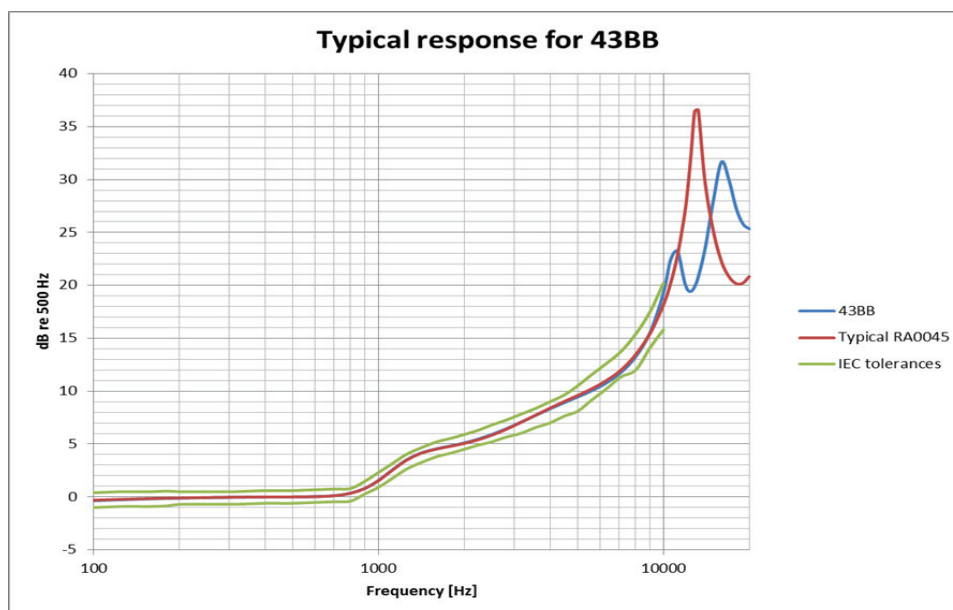
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**Fig. 5.** *Comparison between the transfer impedance of an ideal IEC ear simulator and a typical 43BB low-noise ear simulator*

By using a special low-noise microphone instead of the WS2P microphone the noise floor of the system can be reduced so that it is below the threshold of the human ear, as shown in Fig. 4 on page 2. This means that it is possible to measure levels as low as what can be heard by the typical human ear and thereby give a better indication of the subjective performance of the Device Under Test.

While the standard WS2P has a nominal sensitivity (including preamplifier) in the range of 12.5 mV/Pa, a typical ½" low-noise microphone system has a sensitivity of around 800 mV/Pa, lowering the noise floor to **<**10 dB(A). While this high sensitivity does allow measurements of very low levels, it also limits the upper limit of the dynamic range to about 110 dB SPL.

The low-noise microphone is implemented by making a microphone with a very high sensitivity and low inherent damping, and the mechanical impedance of the diaphragm is therefore very different from the impedance of the WS2P

microphone. This means that the transfer impedance of the IEC 60318-4 ear simulator with a low-noise microphone will be different from the impedance of a standard 60318-4 ear simulator.

Fig. 5 shows a comparison between the typical response of a standard ear simulator and the low-noise ear simulator. It can be seen that the frequency response of the 43BB low-noise ear simulator system is very similar to that of a standard 60318-4 ear simulator below 10 kHz. Above 10 kHz, the differences in the microphone diaphragm impedance results in substantial differences. The standard ear simulator has a high-Q resonance around 13.5 kHz related to the length of the ear canal and the diaphragm impedance. In the low noise version of the ear simulator the single high-Q resonance is replaced by two resonances. A filter unit controls the mechanical resonance of the low noise microphone. The combination of the filter and the low damping of the diaphragm cancels out the high peak of the resonance in the simulator.
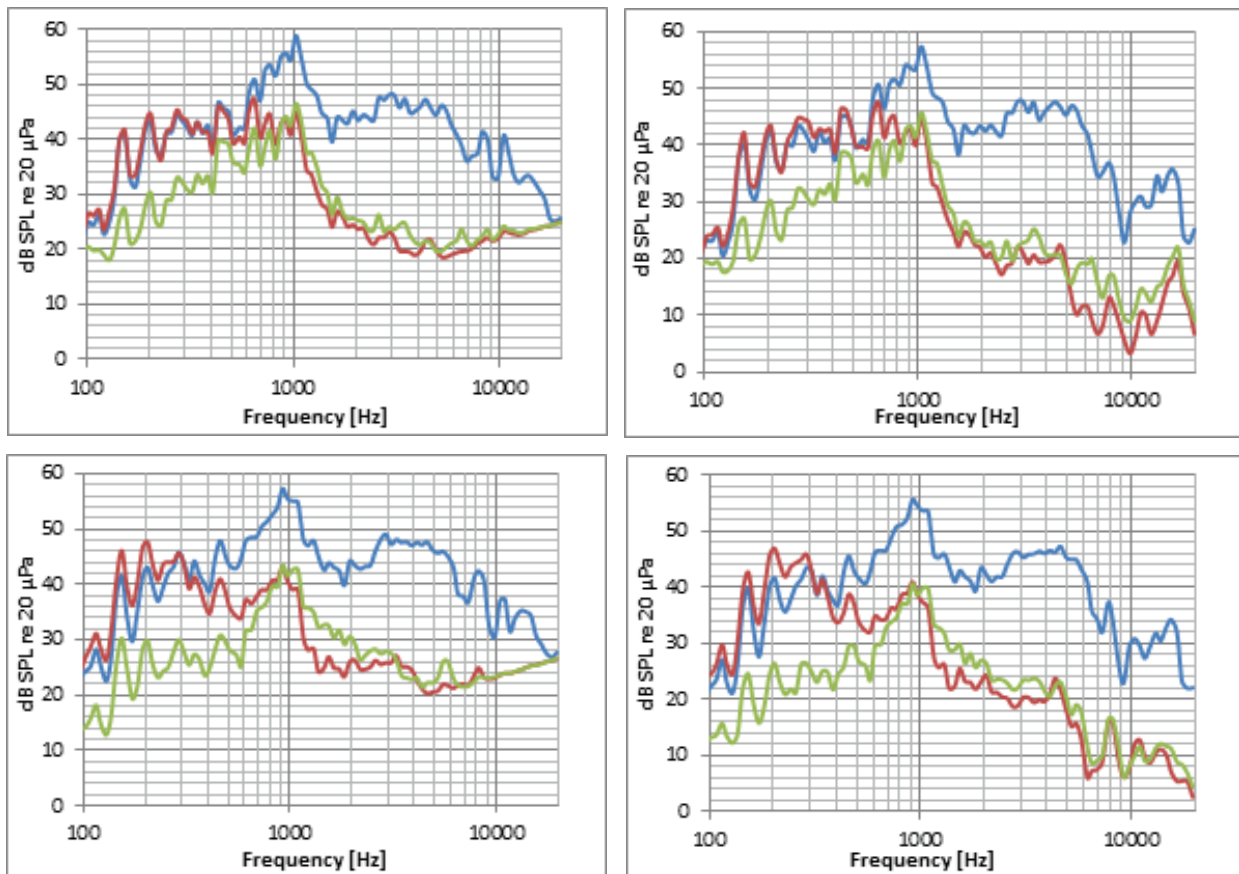
*Fig. 6. ANC headphone comparison. Top two graphs are the low-cost headphones, bottom two are the high-end. Left side graphs are the standard 60318-4 simulator and right side graphs are the low-noise simulator. Blue data is the open ear, red is passive mode and green is with ANC active. High frequency noise can clearly be seen on the standard simulators, while the low-noise simulator can provide measurements at very low levels.*

## Measurement Examples with Low-noise Ear Simulator

In this example, two sets of active noise control (ANC) headphones have been tested with a regular IEC 60318-4 ear simulator and the low-noise simulator. The headphones consisted of a relatively in-expensive ANC set as well as a high-end headset. The headphones were placed on a KEMAR mannequin in a room with acoustic properties like an office or normal listening space. A small speaker provided some background noise at low levels. The resulting frequency response was measured in $1/12^{th}$ octave bands in three different modes; without the headphones on the mannequin (open ear), with the headphones in passive mode (ANC circuit off) and with the noise control on. This will provide a measure of the mechanical as well as the electronic noise dampening capabilities of the headphones.

Fig. 6 shows four graphs of the two headphones. The two top graphs show the results for the low-cost ANC headphone. The top left graph shows the measurements performed with the standard simulator, while the top right graph shows the measurements with the low-noise system. Both measurements clearly show the effect of the mechanical attenuation provided by the headphones. The electronic attenuation of the ANC system can be seen below 1000 Hz. However, at high frequencies the noise floor of the standard simulator masks the effect of the mechanical attenuation. What can also be seen is additional high frequency noise from the ANC system. This noise cannot be measured with the standard simulator, but can be identified with the low-noise system. The relevance of this measurement becomes clear when wearing the headphones since the noise is clearly audible for a subject with normal hearing.
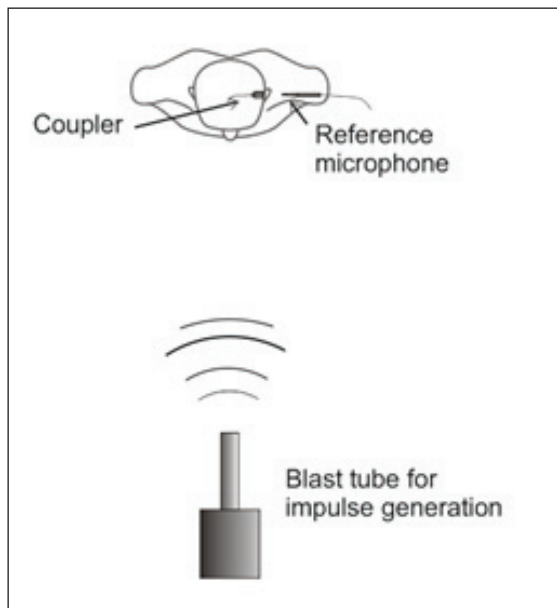
**Fig. 7.** *Typical setup for impulse testing of hearing protectors at high levels*



**Fig. 8.** *Impulse response of ear simulator and HATS. Blue curve: response of reference microphone, Red curve: response of simulator in HATS*

For the high-end ANC headphones shown in the bottom two graphs there is also a clear advantage when using the low-noise system at high frequencies. At both high and low frequencies the self-noise of the standard simulator masks the effect of both the electronic and mechanical attenuation, giving the impression that the system is less effective. For these headphones there is practically no additional noise at high frequencies when the ANC system is on.

Besides noise measurements at low levels, the system can be used for measurements of harmonic distortion (THD) and Rub & Buzz measurements at low input levels.

### Ear Simulator for High Level Measurements

Measurements of high levels are important when for example evaluating hearing protectors, especially for the attenuation of high level impulsive noise. In this case the standard ear simulator is limited to levels below approximately 160 dB SPL.
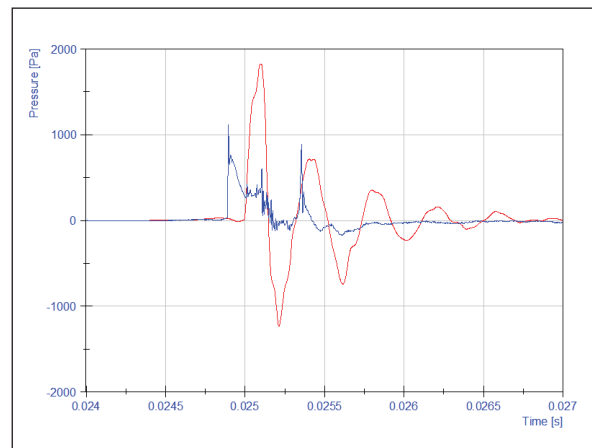
Fig. 7 shows a typical setup for impulse testing of hearing protectors at high levels. The blast tube creates a high level acoustic shock wave by expanding compressed air. The shock wave is measured simultaneously with a 1/8" reference microphone and a occluded ear simulators mounted inside a Head and Torso Simulator (HATS). The resulting signals from the blast tube as measured with the reference microphone and the ear simulator is seen in Fig. 8, and it can be seen that the ear simulator signal is amplified by approximately 6 dB. This is caused by the diffraction around the Head and Torso simulator and the ear-canal resonance.

The amplification of the acoustical signal in the ear simulator means that the dynamic range requirements are more demanding than for the external reference microphone. For testing of high level impulses like for example gunshots, which may easily reach levels above 170 dB, the standard ear simulator WS2P microphone will be overloaded.
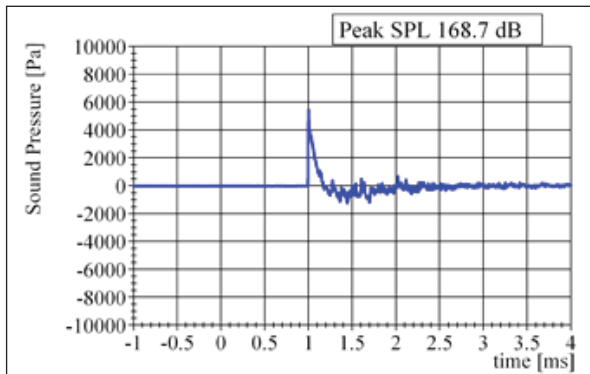
**Fig. 9.** *Typical high level impulse from rifle*

This type of testing is described in details in the American standard ANSI S12.42 *"Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive noise Using Microphone-in-Real-Ear or Acoustic Test Fixture Procedures"*. This standard includes a detailed description of a special Head and Torso simulator with ear simulators based on a WS3P type microphone.

Fig. 10 shows such a Head and Torso simulator with ¼" pressure type microphones with a 3% distortion level at 172 dB. By accepting 10% distortion, the High Level Ear simulator can measure levels up to 178 dB SPL. So as to not overload the system electrically when exposed to signals greater than 170 dB, the microphone used in the high level ear simulator is made to be very insensitive (in the order of 1.6mV/Pa). That, however, also impacts the noise floor of the ear simulator, which is now at ≈44dB SPL. For even higher levels a version

of the ear simulator that can measure up to an SPL level of 181 dB is available.



**Fig. 10.** *Head and torso for high level hearing protector test*

Fig. 11 shows a typical frequency response of a high level ear simulator based on a ¼" pressure microphone. It can be seen that the frequency response is within the tolerance limits of the IEC standard, however the resonance frequency is slightly changed due to the higher diaphragm impedance of the ¼" WS3P microphone compared to the softer ½" WS2P microphone diaphragm.
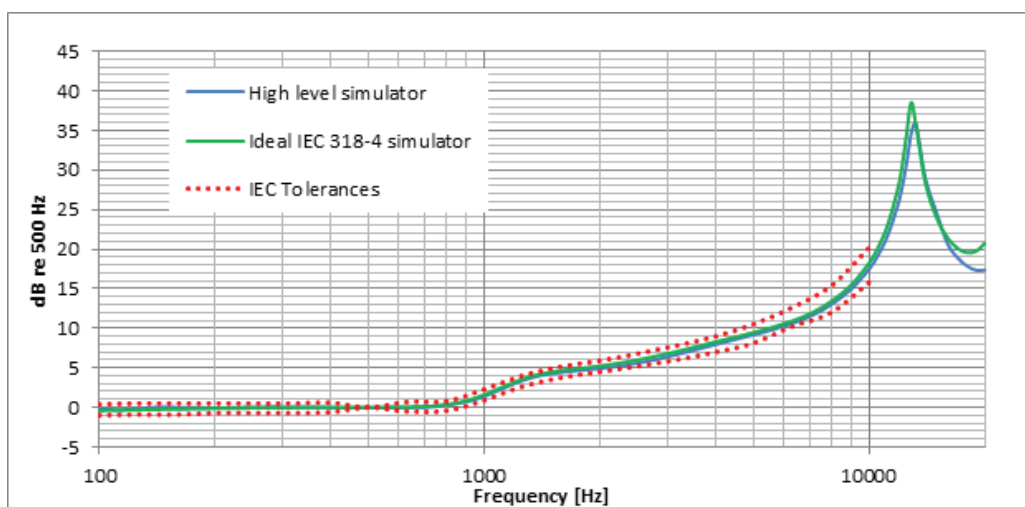


**Fig. 11.** *Typical frequency response of high level ear simulator based on a ¼" pressure microphone*

## Anthropometric Ear Canal and Pinna

The shape of the pinna and ear canal simulators are described in detail in the IEC 60318-7 standard. The shape of the pinna is based on human subjects and considered realistic.

However, the ear canal extension connecting the pinna to the ear simulator is either cylindrical or conically shaped and thus far from the complexity of a human ear canal. While the cylindrical ear canal is relevant for testing hearing aids, often paired with a standardized ear mold, it can be difficult to obtain reliable, repeatable measurements with ear-bud headphones and in-ear hearing protectors. Furthermore, the compliance and pliability of the standardized pinna may be accurate in one dimension, but definitely not when it comes to collapsing towards the head. This presents an added obstacle when measuring devices intended to go on or over the ear, as the pinna protrusion and stiffness can prevent a good seal and therefore an accurate measure of low frequency performance – both in terms of audio reproduction and ambient noise reduction.

A major project from Denmark's Technical University (DTU) has mapped the scope of the human ear canal. Based on 300+ 3D scans of human ear canals, a mean human ear canal has been developed[4].

This ear canal shows all the characteristics of a human ear canal – it has the 1st and 2nd bend and the oval interface with the concha – but it cannot readily be interfaced with the ear simulator and pinna simulator of the standardized ear due to the angle with which the ear simulator meets the ear canal.

In humans, the tympanic membrane is at an angle to the ear canal, where the ear simulator – and the diaphragm of the microphone – is perpendicular to the ear canal.

Therefore, while the ear canal in the anthropometric ear preserves the overall characteristics of the mean human ear canal, some tweaking has been required to adapt the ear canal to interface with the entrance to the IEC 60318-4 ear simulator. In addition to the anatomically correct ear canal, the standard pinna has been changed to provide better flexibility of the outer ear. The pinna and ear canal are shown in Fig. 12 with the interface to the 60318-4 simulator.
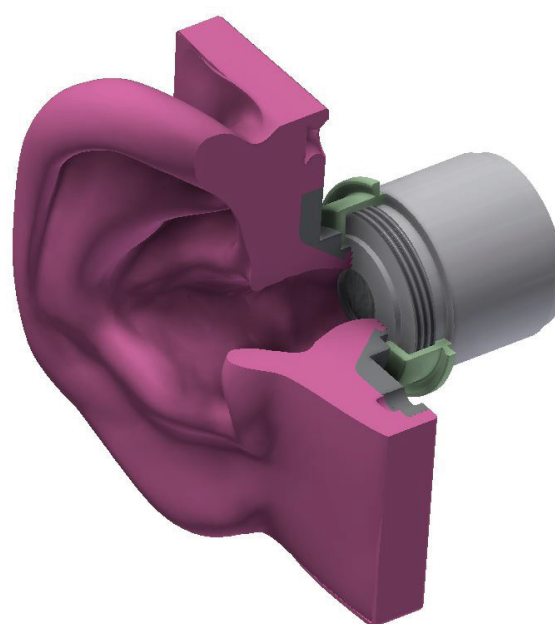


**Fig. 12.** *Cut-through of the anthropometric pinna and ear canal showing interface with 60318-4 ear simulator*

Although changes have been made to both the ear canal and the outer ear and pinna, the overall standardized shape of the ear has been maintained.
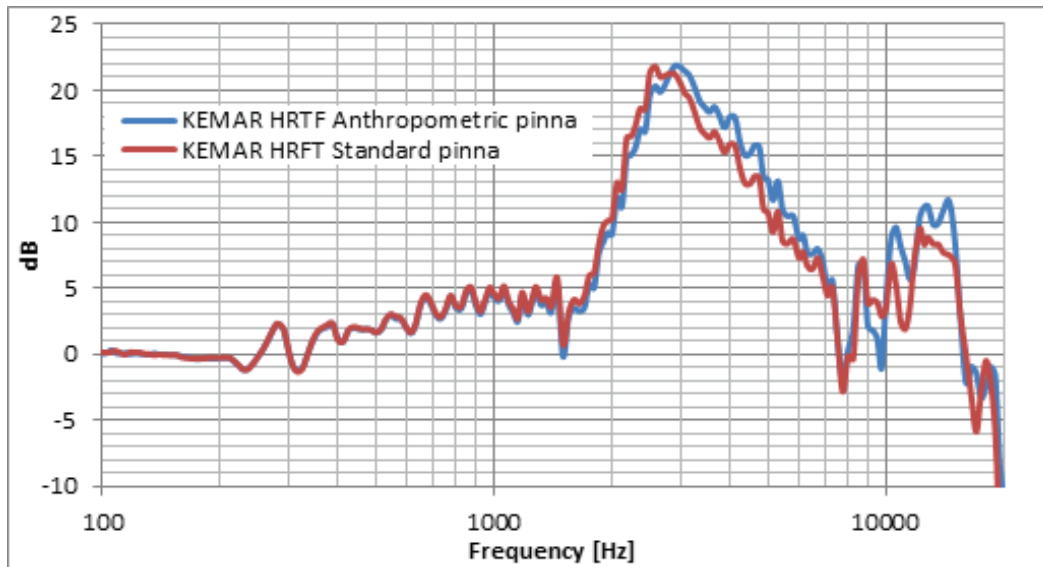
**Fig. 13.** *Free field HRTF of left ear on KEMAR measured with the standard pinna and the anthropometric pinna and ear canal. In both cases a standard 60318-4 ear simulator was used.*

Fig. 13 shows a comparative measurement of the free field HRTF of KEMAR at 0º incidence. The measurement compares the standard pinna and cylindrical ear canal to the new anthropometric ear canal and pinna. In both cases a standard IEC 60318-4 ear simulator was used. The measurements show that only minor changes in the HRTF can be seen. This ensures that legacy measurements with KEMAR and standard pinna can be compared to the new ear.

**In-Ear Testing**
Repeatability in measurements is a major concern when testing in-ear headphones.

When testing ear-buds, insertion depth and sealing can introduce a large spread in the frequency response from insertion to insertion at either high or low frequencies.

When measuring with either the standard cylindrical or the conically shaped ear canal, several problems may arise: Firstly, it is difficult to control the insertions depth resulting in shifting resonances at high frequencies due to the changes in canal length. Secondly, the sealing of the ear-bud to the canal is either hard to re-

peat or unrealistic compared to the more complex oval shaped entrance to the human ear.

By measuring with a more realistic ear canal it is possible to obtain better consistency from insertion to insertion.

Fig. 14 shows a typical example of a modern ear-bud. While the forward angle of the ear-bud improves fit on a human subject it makes it very hard to place in the standard conical or cylindrical ear canals.



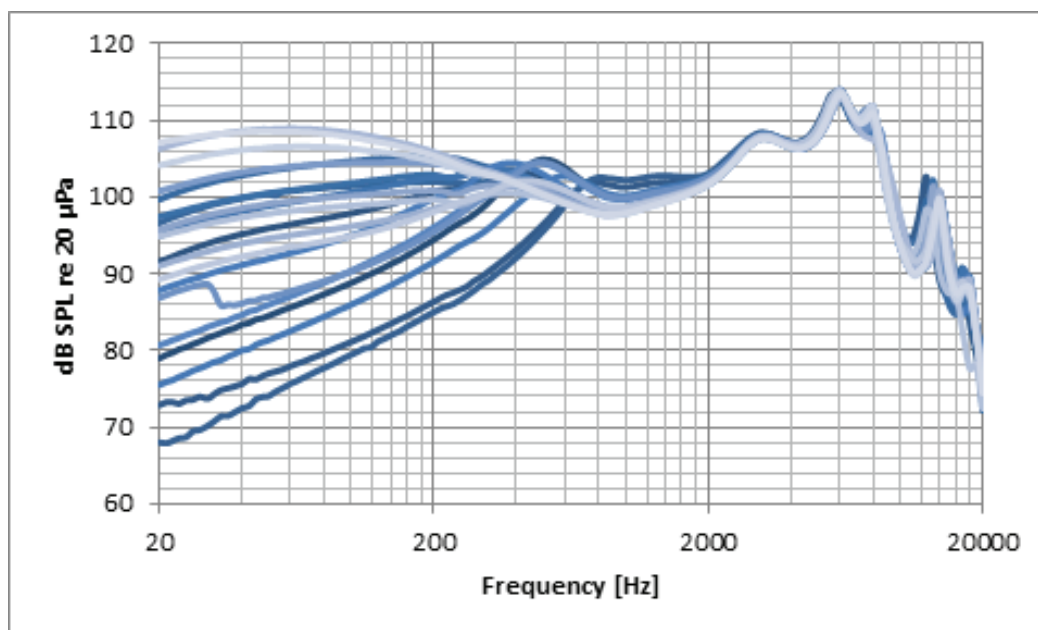**Fig. 14.** *Example of in-ear product (left side, top view)*

*Fig. 15. Twenty fittings of ear-bud in conical ear canal with standard ear simulator*
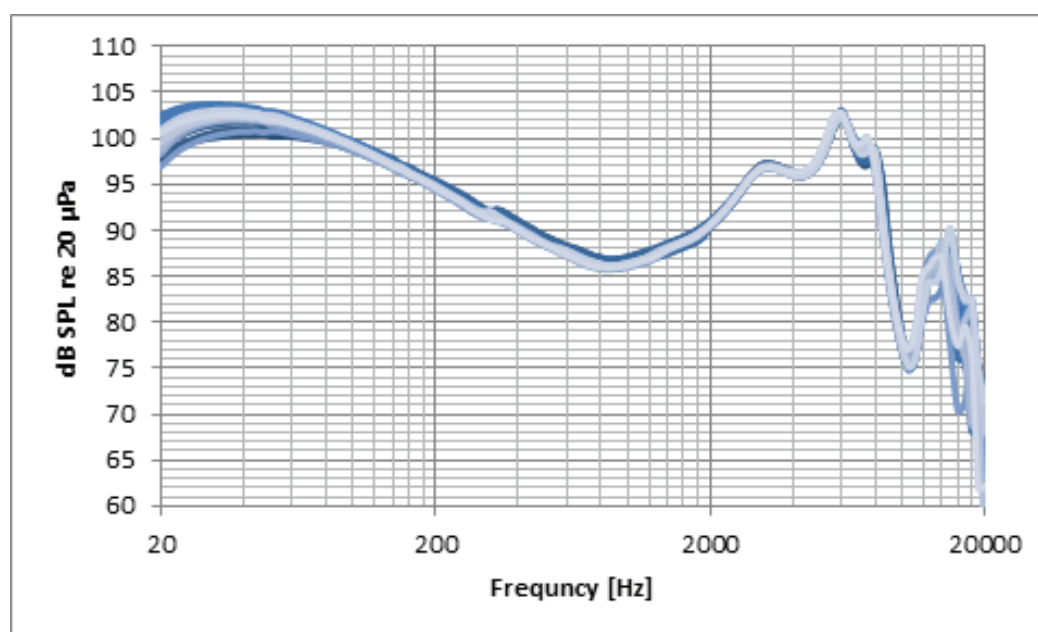


*Fig. 16. Twenty fittings of ear-buds in anthropometric ear canal and low-noise ear simulator*

To compare the repeatability of fitting the ear-bud in a KEMAR mannequin, the ear-bud was fitted 20 times in a conical metallic ear canal and 20 times in the anthropometric ear canal. The frequency response of the ear-bud was measured each time using a swept sine with 1/12th octave resolution. Fig. 15 and Fig. 16 show the difference between the traditional conically shaped ear canal and the anthropometric ear canal. Clearly there is an advantage when using the anthropometric system, particularly the seal and thus the response at low frequencies shows increased repeatability.
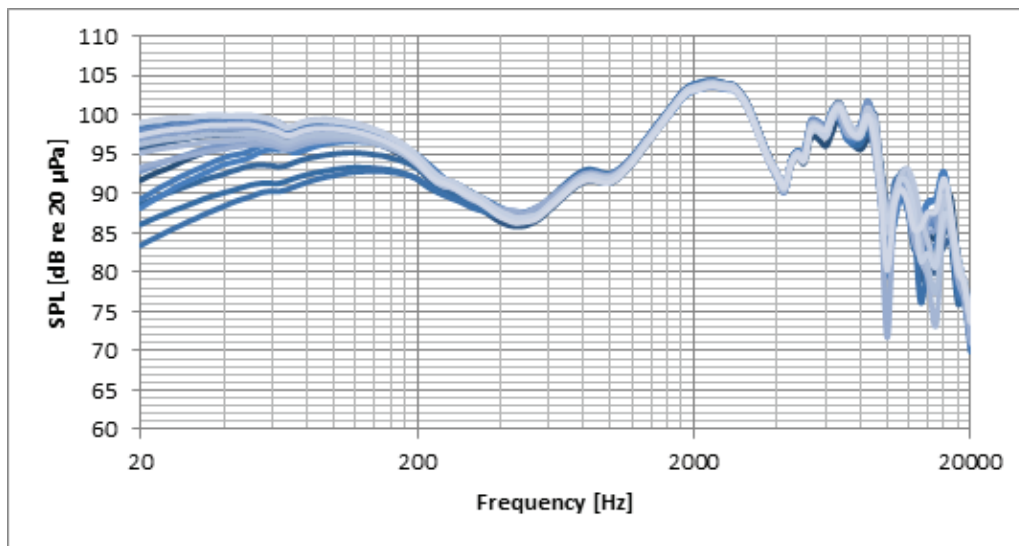
**Fig. 17.** *Twenty measurements with a high quality supra-aural headphone on KEMAR with the standard pinna and ear simulator*
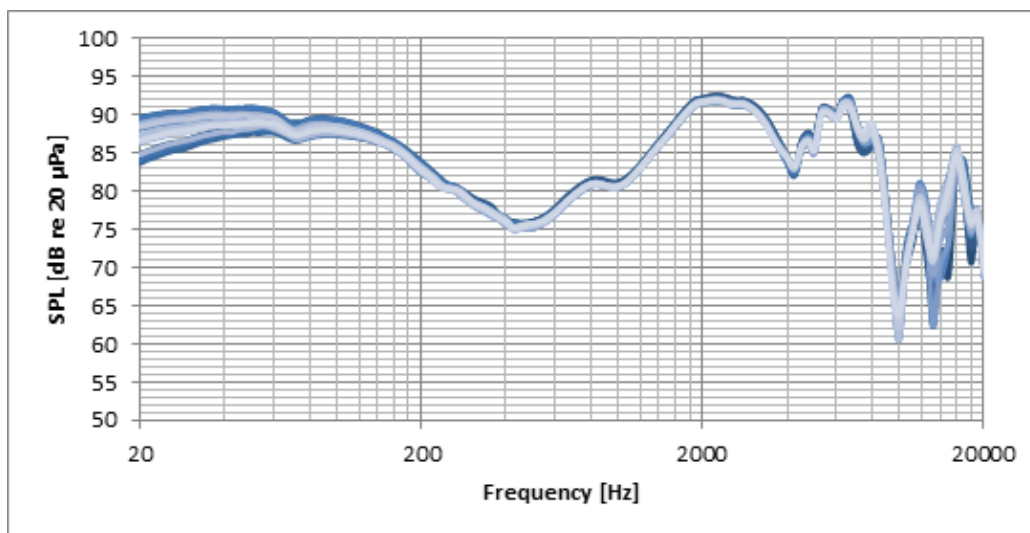


**Fig. 18.** *Twenty measurements with a high quality headphone on KEMAR with the anthropometric pinna and low-noise ear simulator*

### Circum-/supra Aural Testing

When measuring the frequency response of either circum-aural or supra-aural headphones reliable and repeatable tests are essential. The anthropometric pinna has more realistic compliance of the pinna compared to the standardized pinna to improve the collapsibility of the pinna when mounting headphones. Fig. 17 and Fig. 18 show the results when testing a set of high quality supra-aural headphones. The headphones where placed 20 times on a KEMAR with the standard pinna and 20 times on a KEMAR with the new anthropometric pinna. When comparing the results from the standard ear to the more flexible pinna, the improve-ments in the low end are immediately visible. Not only does the repeatability improve at low frequencies, but we also see a more consistent response at the higher end. As a function of position, the new pinnae allow for the transducer to ear drum placement to be more reliable, hence the added advantages at the higher end.

When using the new pinnae with the low-noise ear simulator, we see an additional effect of the split resonance and smoother response: the high frequency output tends to be ≈10dB higher and more stable. This allows for more clarity on the headphone output and a greater confidence in the measurements above 10 kHz.

## Conclusion

The IEC 60318-4 (711) ear simulator is used extensively and offers a lot of benefits for electro-acoustic testing, and now several of its limitations have been overcome.

This paper presented two different ear simulators for very separate measurement cases. As industries and needs evolve, the modified ear simulators address the challenges of measuring at very low levels and very high levels, while still maintaining the familiar 711 ear simulator frequency response up to 10 kHz.

While strictly speaking not IEC 60318-4 compliant, due to the choice of microphone, the modified ear simulators can be considered drop-in replacements for those looking to measure in these extended areas.

Also, a more realistic ear canal combined with a more flexible pinna can provide greater repeatability in measurements of in-ear, circum-aural or supra-aural headphones.

## References

(1) IEC Standard 60318-4: *Electroacoustics – Simulators of human head and ear – Part 4: Occluded ear simulator for the measurement of earphones coupled to the ear by ear inserts*

(2) ANSI/ASA Standard ANSI/ASA Standard S12.42-2010: *Method for the measurement of insertion loss of hearing protection devices in continuous or impulsive noise using microphone-in-real-ear or Acoustic test fixture procedures*

(3) IEC Standard 61094-4: *Measurement microphones - Part 4: Specifications for working standard microphones*

(4) R. R. Paulsen: *Statistical Shape Analysis of the Human Ear Canal with Application to In-the-Ear Hearing Aid Design*, Informatics and Mathematical Modelling, Technical University of Denmark, Building 321, Richard Petersens Plads, DK-2800 Kgs. Lyngby, 2004 [available online at *http://www.imm.dtu.dk/~rapa/research.html*].