Application Note: Headphone Electroacoustic Measurements

Introduction

In this application note we provide an overview of the key electroacoustic measurements used to characterize the audio quality of headphones and earphones[1] intended for listening to music and other full-band audio program material. These measurements also apply also to headsets[1], but only insofar as they are used as headphones[2].

Due to the close coupling of earphones to the ears and the acoustic transmission paths involved, headphone measurements are complicated. In this article, we'll discuss these challenges, types of headphones, measurement standards, headphone acoustics, acoustic test fixtures required for measuring headphones, and the practical aspects of headphone measurements. We'll also focus on objective measurements.

The following electroacoustic headphone measurements are covered in this application note:

- Frequency Response
- Electrical Impedance
- Input voltages
- Sound Pressure Level
- Distortion
- Noise Attenuation
- Crosstalk Attenuation

Industry Standards

When conducting performance measurements, it is usually preferable to adhere to industry standards. Ideally, standards represent consensus among industry experts concerning measurement conditions and recommended practices that will help to ensure that devices are tested in a meaningful and repeatable way. The key international standard covering headphone measurements—and the focus of this application note—is *IEC 60268-7, Sound system equipment, Part 7: Headphones and earphones* [1].

Earphone Types

Earphones are classified according to their shape and how they couple to the ear, as follows: (See Figure 1).

a) Circumaural earphones completely surround the pinna (outer ear) and rest on the surface of the head surrounding the pinna. They may touch the pinna, but do not significantly compress it.
b) Supra-aural earphones rest on the pinna.

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[1] IEC 60268-7 [1] defines **earphone** as an electroacoustic transducer intended to be closely coupled to the ear, **headphone** as an assembly of one or two earphones which may or may not be mounted on a headband and **headset** as a headphone assembly equipped with a microphone.

[2] Measurements to characterize the quality of headset voice communication are the domain of telephony standards such as IEEE 269 [2] and are beyond the scope of this document.

c) Intra-concha earphones are small earphones intended to rest within the concha cavity of the ear (the hollow just outside the ear canal).
d) Insert earphones are small earphones which are intended to partially or completely enter the ear canal.
e) Supra-concha earphones (not shown in Figure 1) are intended to rest upon the ridges of the concha cavity.

Earphones are further classified as acoustically open or closed. Open earphones (also called nominally unsealed) intentionally provide an acoustic path between the external environment and the ear canal. Closed (or nominally sealed) earphones are intended to prevent any acoustic coupling between the external environment and the ear canal.

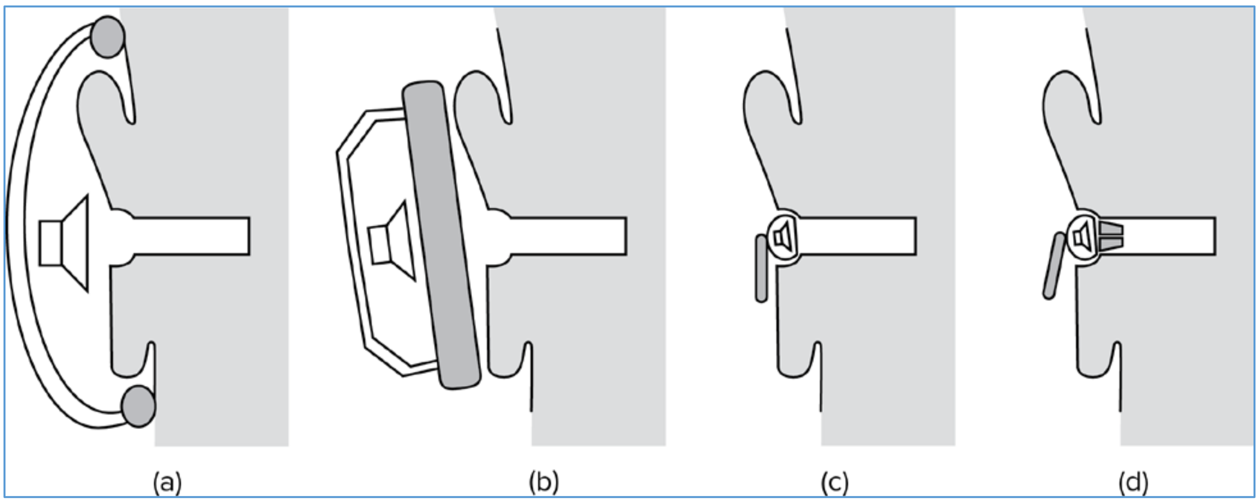

Figure 1. Headphone types (a) circumaural, (b) supra-aural, (c) intra-concha, and (d) insert (adapted from [1]).

Headphone Measurements and Acoustics

Sound Fields—Free and Diffuse

When considering headphones and earphones, the concept of sound fields is important, especially the opposing extremes of free and diffuse fields. A free field is defined as an environment that is completely free of acoustic reflections, at least within the frequency range of interest. The frequency response of a loudspeaker must be measured in a free field. In this environment, sound waves radiate from the loudspeaker and are never reflected back, such that a measurement microphone in the sound field can only measure direct sound. In practice, loudspeaker measurements are typically conducted in an anechoic chamber, which is a free field at frequencies above a minimum frequency that depends on the size of its absorptive wedges.

A diffuse field is the opposite of a free field: In a diffuse field, sound waves are traveling randomly in all directions with equal probability and the long term rms sound level is approximately the same at all locations. A diffuse sound field can be created in a reverberation chamber (a special room which has hard, acoustically reflective surfaces that absorb almost no sound). For example, when measuring ambient noise attenuation of headphones, a diffuse sound field is typically created by loudspeakers generating random noise in a reverberation chamber.

Frequency Response

> *Frequency response is the single most important aspect of the performance of any audio device. If it is wrong, nothing else matters.* (Floyd Toole, 2009 [4])

Frequency response is certainly an important (and widely discussed) measurement for headphones and loudspeakers; it is generally thought to be the characteristic that is most indicative of perceived quality. Frequency response is a transfer function measurement. For electroacoustic devices, it represents the magnitude and phase of the acoustic signal radiating from the device per unit voltage input, as a function of frequency, as measured at a point in space. Devices are often compared in terms of the "shape" of their frequency response curves, which refers to the magnitude response only (not phase), and in addition normalizes the magnitude to a reference value. For example, the response magnitude might be normalized to its value at some reference frequency, say 1 kHz, such that the normalized curve passes through 0 dB at 1 kHz.

For audio electronics, a flat frequency response is quite achievable. For example, almost any audio amplifier will have a flatness of less than ±1 dB within the audio band (20 Hz to 20 kHz); even ±0.1 dB is not uncommon.

In the case of loudspeakers, achieving a smooth, flat frequency response is challenging, for a variety of reasons. A review of several popular consumer loudspeakers showed deviations from flatness (50 Hz to 20 kHz) of up to 20 dB [4]. Nevertheless, it is possible to achieve a relatively smooth and flat response for loudspeakers, and a deviation from flatness of ±3 dB is considered "respectable." Perhaps in recognition of the fact that a flat response is preferable for loudspeakers, the IEC 60268-5 standard on loudspeakers specifies a metric called the "Effective Frequency Range," which is a measure of the frequency range over which a loudspeaker's frequency response deviates from a flat line through the point of maximum level response by no more than 10 dB.

The Head Related Transfer Function

Headphone and earphone measurements are complicated by the interaction of the sound field with the ears. Figure 2 illustrates the concept of the Head Related Transfer Function (HRTF). The blue curve labeled "Microphone" in Figure 2 represents the frequency response of a loudspeaker (equalized to have a flat response) as measured by a microphone on-axis in a free field. The red curve is labeled "Ear at DRP", which stands for Drum Reference Point — a point at the end of the ear canal representative of the ear drum. This curve represents the frequency response of the same flat loudspeaker that would be measured at the ear drum of a typical person positioned at the same location in the free field as the original microphone[3]. The red "Ear at DRP" curve is an HRTF. It includes the effects of the person's body, head, pinna and ear canal on the acoustic signal as it travels from the source through the air to the ear drum. Notable and characteristic features of this HRTF are a broad peak with a gain of about 17 dB centered at approximately 3 kHz and a notch centered at approximately 8 kHz. The peak at 3 kHz is a result of two effects cascaded together: (1) an acoustic resonance of the open ear canal resulting in a boost of about 10 dB and (2) the obstacle effect of the head which causes a boost of about 10 dB centered at 4 kHz [5]. The notch at 8 kHz is referred to as the "pinna notch" and is caused by destructive

[3] The Ear at DRP data in Figure 2 is for a special manikin used for acoustic research called a Head and Torso Simulator (HATS), designed to simulate the sound pick-up characteristics and the acoustic diffraction produced by a median human adult [3].

interference between sound waves that travel directly to the ear drum and waves that reflect off features of the pinna.

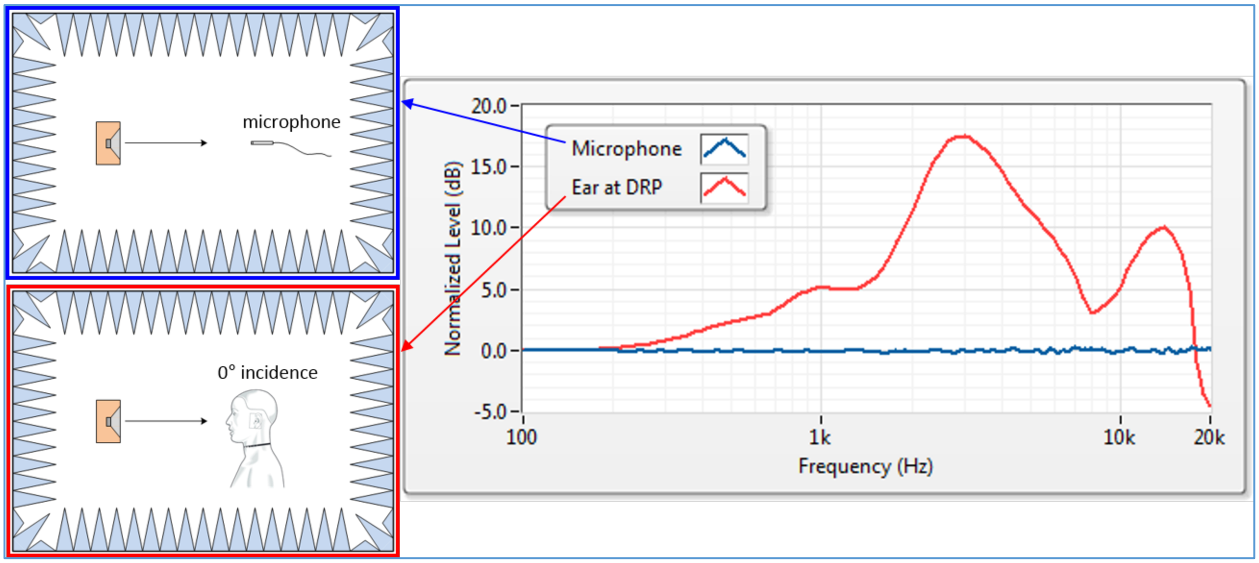

Figure 2. Frequency response of a loudspeaker equalized flat in a free field as measured by a free field microphone and an in-ear microphone at the Drum Reference Point or DRP (DRP data from [3]).

The HRTF shown in Figure 2 is for one specific direction with respect to the subject: directly in front of the subject and in the horizontal plane. Due to the shape of the pinna, the head and the torso, there is a different HRTF for every position of a sound source in 3-dimensional space around a listener. For example, Figure 3 shows four HRTFs for positions 90 degrees apart in a horizontal plane around a KEMAR[4] manikin. These differences in the HRTFs are a key part of our highly developed ability to pinpoint the location of sounds in the environment.

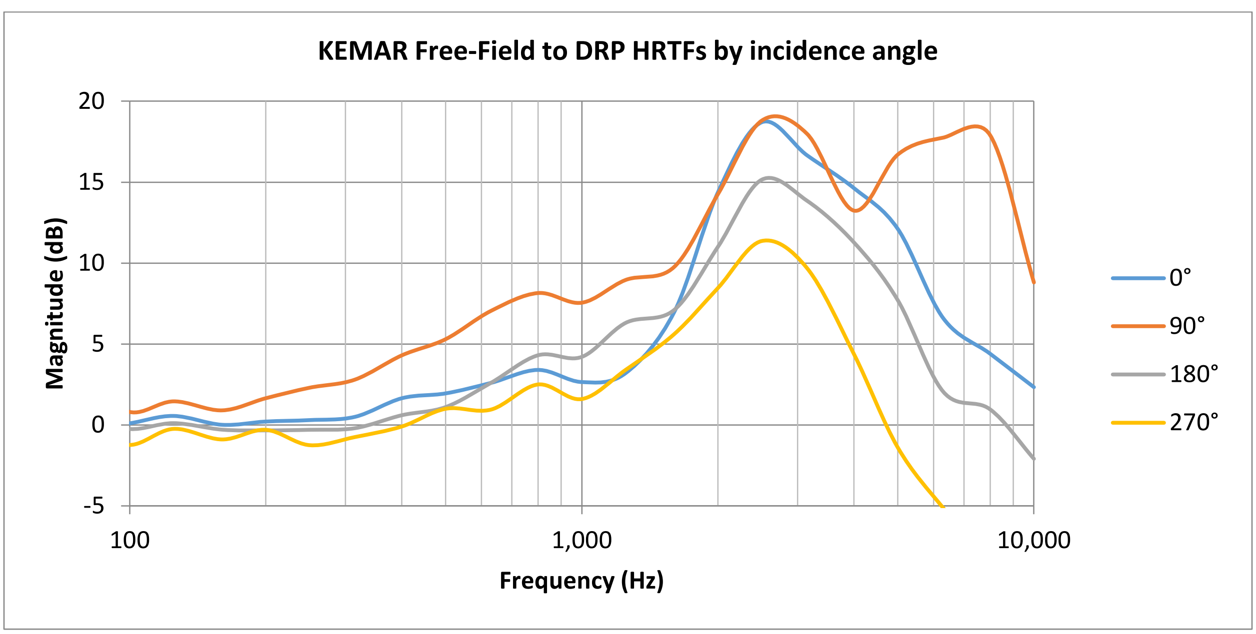

Figure 3. HRTFs for 4 positions 90 degrees apart around a KEMAR manikin in the horizontal plane (data provided by G.R.A.S. Sound and Vibration).

[4] A KEMAR manikin is a type of head and torso simulator

If a sufficiently large number of HRTFs representing all positions around a subject in a free field are averaged together, the resulting frequency response curve approaches the diffuse field response. For example, Figure 4 shows the average of the four HRTFs from Figure 3, with a diffuse field HRTF. Note that with only 4 HRTFs included, the average response is already remarkably close to the diffuse field response. The diffuse field HRTF represents the frequency response that would be measured in the ear canal due to an ideally flat loudspeaker in a diffuse sound field.

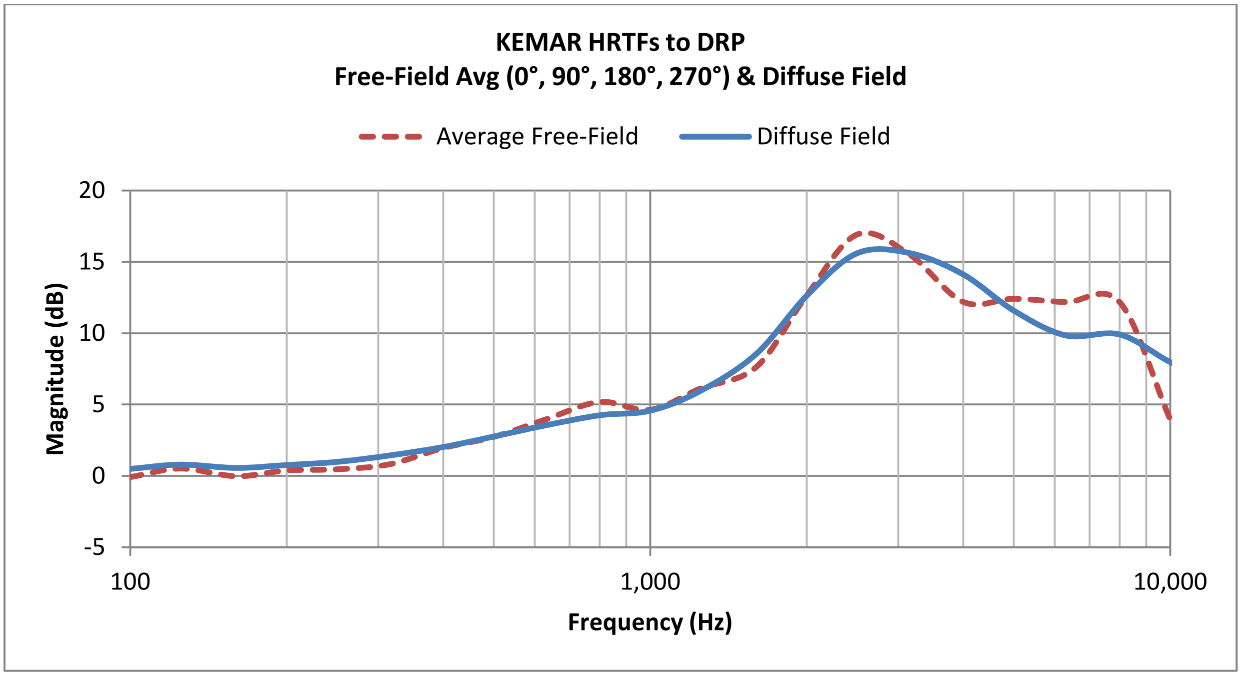

Figure 4. Average of the 4 HRTFs in Figure 3 with the Diffuse Field Response

Acoustic Test Fixtures for Measuring Headphones

Because headphones and earphones are closely coupled to the ear, it is not possible to measure their frequency response in a free field. Some form of acoustic test fixture must be used which simulates (1) the acoustic impedance (or load) presented to the headphone by the human ear, and (2) the interaction of the earphone with the pinna and head (or concha and ear canal in the case of insert earphones). This is usually accomplished using an acoustic test fixture (ATF) with one or more occluded ear simulators. The occluded ear simulator is a special type of coupler designed to have an acoustic impedance equivalent to that of a typical human ear. It contains a calibrated measurement microphone positioned to measure sound at a point representative of the ear drum.

A Head and Torso Simulator (HATS) is one type of acoustic test fixture. A HATS is a manikin that extends upward from the waist to the top of the head, designed to simulate the sound pick-up characteristics and the acoustic diffraction produced by a median human adult [6]. A HATS may be equipped with one or two Type 3.3 ear simulators [7], which consist of an IEC 60318-4 (formerly IEC 60711) occluded ear simulator combined with an ear canal extension and a pinna simulator. Figure 5 shows one example of a HATS called KEMAR[5], manufactured by G.R.A.S. Sound and Vibration. HRTFs for the three leading HATS systems currently available have been published in a paper from the Danish Technical University [13].

[5] KEMAR is an acronym which stands for Knowles Electronics Manikin for Acoustic Research.

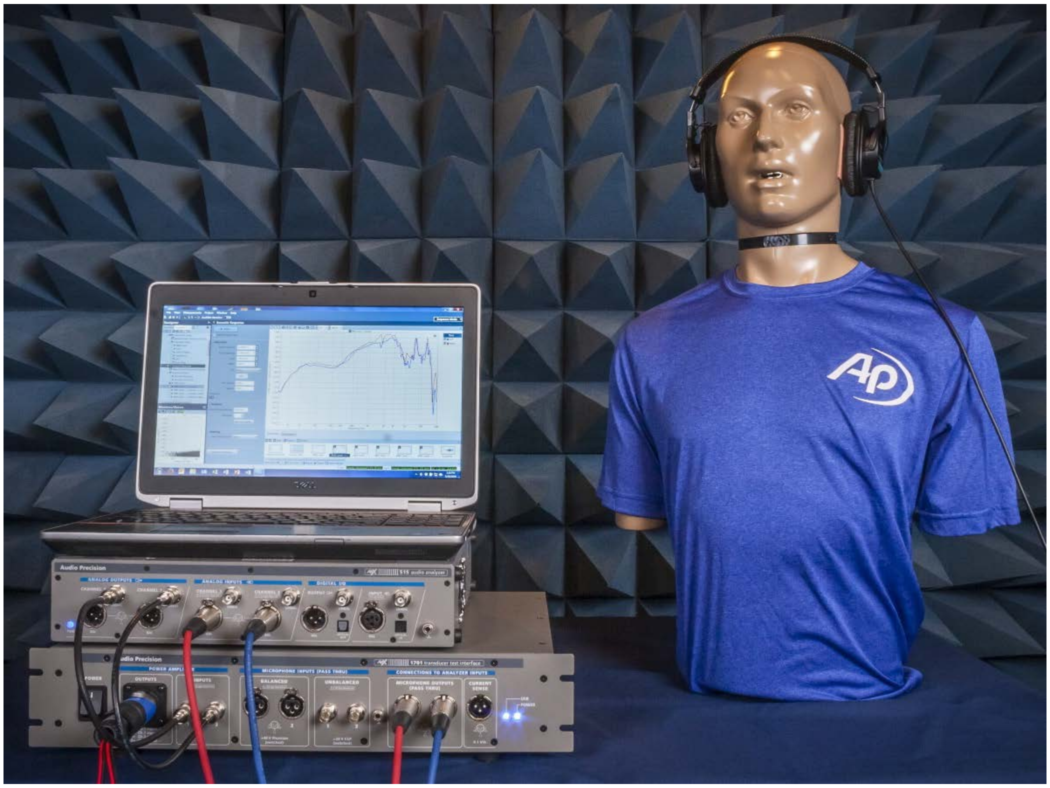

Figure 5. An example of a Head and Torso Simulator called KEMAR, made by G.R.A.S Sound and Vibration.

While a HATS can definitely be used for headphone measurements, they are relatively expensive (the HATS in Figure 5 costs approximately $22,000 USD, when configured with two ear simulators). In addition, the complete functionality of a HATS is not really required for testing headphones, because the close coupling of the earphones to the ears removes most of the head and the entire torso from having any effect on the acoustic sound field.[6] As a result a simpler acoustic test fixture can be used to test headphones. One example of such an ATF is the Audio Precision AECM206, shown in Figure 6. Key dimensions of the AECM206 approximate those of an average adult human head, as described in ISO 4869-3 [17]. The AECM206 is equipped with two IEC 60318-4 [20] ear simulators and anatomically shaped pinna simulators [7], and it provides a high degree of acoustic noise isolation. As such, an AECM206 headphone test fixture is well suited to testing stereo headphones, especially those which use a headband or neckband. It can also be used for insert-type earphones, and its high noise isolation makes it useful for testing headphones and earphones with active noise cancelation. (An AECM206 headphone test fixture costs approximately $11,000 USD.)

[6] Note: For testing the microphone function of a headset, a HATS *is* required, to simulate the effects of the head and torso on the acoustic sound field around the microphone. Furthermore, the HATS would need to be equipped with a mouth simulator, which adds additional cost.

Figure 6. Audio Precision AECM206 headphone test fixture.

Two simpler yet acoustic test fixtures are shown in Figure 7. The ATF on the left is called an “Ear and Cheek Simulator”. It has one Type 3.3 ear simulator and a flat surface around the pinna that a circumaural earphone can seal against. The use of the word “cheek” in the name is a bit confusing, because what the fixture really simulates is not really the cheek, but rather the part of a human head surrounding the outer ear that a circumaural earphone would seal against. This ATF can be used to test any of the earphone types listed above, but of course only one side of a pair of stereo headphones or earphones can be tested at one time. It is also less convenient for testing headphones which have a headband or neckband; it can be difficult to fit an earphone on the fixture while attached to the headband, and in some cases the earphone must be removed from the band. Also, the clamping force of the headband or neck band must be simulated using the included spring-loaded clamp. The approximate cost of each of the ATFs in Figure 7 is $5,000 USD.

In addition to the convenience for testing headphones with a headband, one advantage of using an ATF with two ear simulators is that dual-channel measurements like Left/Right tracking and crosstalk are possible.

Figure 7. G.R.A.S. Type 43AG Ear and Cheek Simulator (left) and Type 43AC Artificial Ear.

For testing insert type earphones, an acoustic test fixture like the one shown on the right side of Figure 7 can be used. In this case, the pinna and the surrounding “cheek” plate are not required, because the insert earphone is inserted directly into the ear canal. This ATF has an external adaptor designed to simulate the interaction of an insert earphone with the outer ear canal. The spring-loaded clamp can be used to simulate the pressure of a headband or neck band, if appropriate. It should be noted that the frequency response of insert earphones measured with this ATF will be different than that measured on an ear simulator with pinna and ear canal extension.

Design Targets for Headphone Frequency Response

Free Field Response

Considering Figure 2, one can see that it would be reasonable to conclude that for an earphone to sound like an ideally flat loudspeaker in a free field (i.e., with minimal spectral coloration), its frequency response should closely match the HRTF for the position directly in front of the listener. This is known as the free field response design target. This target is used for telephone handsets and headsets [3], with the intended goal being that a telephone conversation using a headset or handset should approximate the acoustical experience of a face-to-face conversation in a free field[7]. Apparently, free field response was also the design target for high quality headphones in the early days of the audio industry [8].

Diffuse Field Response

In the 1980s, the diffuse field was added as a reference condition to audio standards for studio monitor headphones [9]. In this case, the target response curve for headphone design would be the diffuse field response curve in Figure 4. This change was probably made in recognition of the fact that listening environments are never anechoic, and a diffuse field is a closer approximation to a typical listening environment than a free field.

[7] IEEE 1652 [3] uses the concept of the Orthotelephonic Reference—a face-to-face conversation in a free field at a distance of one meter.

Recent work on this subject indicates that listeners prefer alternatives to the free field and diffuse field headphone target frequency response curves described above. One recent study [10] found that in general, trained listeners preferred a headphone target response that corresponds to a flat loudspeaker calibrated in a reference listening room over either a free field or diffuse field target response. This makes sense when you consider that stereo recordings are optimized for enjoyment when played through loudspeakers in a room.

When considering the frequency response of headphones measured on an ATF with ear simulators, it is important to keep in mind that the target response is not flat. There are two options in this regard. The first option is to display the design target curve(s) on the same graph as the measured (normalized) frequency response. This is illustrated in Figure 8, which shows the frequency response of one model of a circumaural headphone (Headphone 1)[8] as measured on an ATF plotted with the diffuse field and free field design target curves. With this approach, one can mentally compare the measured curve to the target curve when evaluating the measured frequency response.

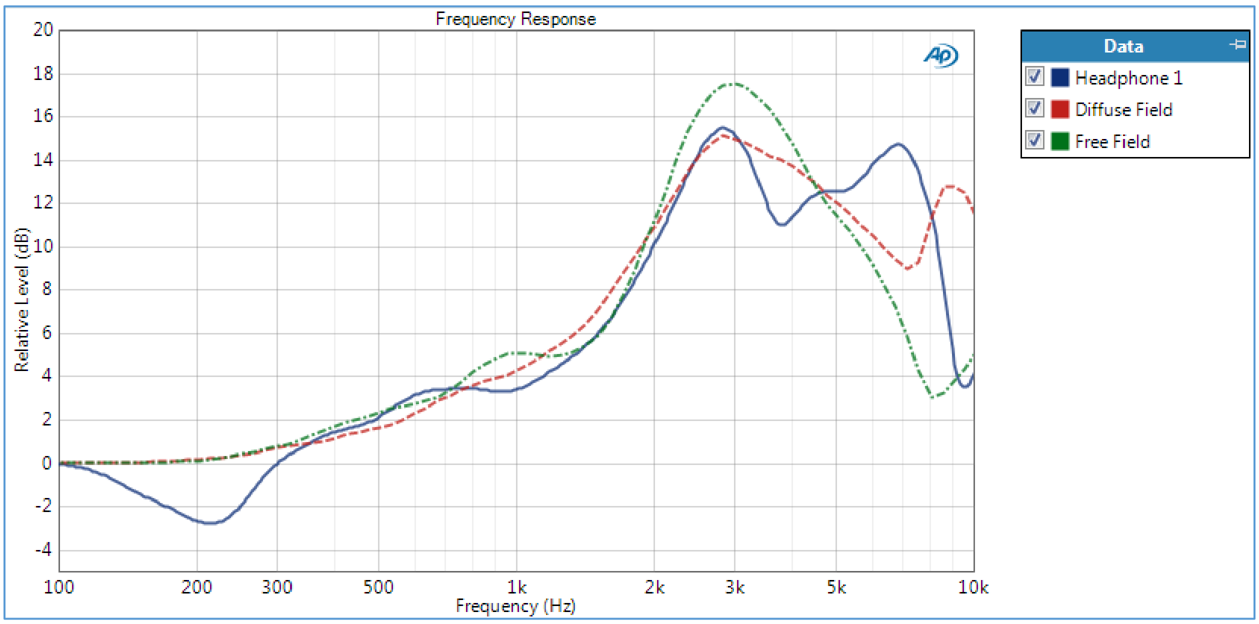

Figure 8. Frequency response of Headphone 1 (a circumaural, closed headphone) with the Diffuse Field and Free Field response curves.

The second approach for evaluating measured headphone frequency response is to "correct" or refer the measured response to the target response. This is accomplished by inverting the target response curve and applying it as an EQ curve to the measured response. This is illustrated in Figure 9, in which the headphone response measured in Figure 8 was corrected to the diffuse field and the free field. With this approach, the corrected response of a headphone that matches the target response perfectly would be a flat line at 0 dB.

[8] Headphone 1 is a circumaural, closed headphone described by the manufacturer as a headphone with "… a large diaphragm designed for professional studio and live broadcast applications". It has a list price of $130 USD. It is used throughout this document as the subject of various measurements for illustration purposes.

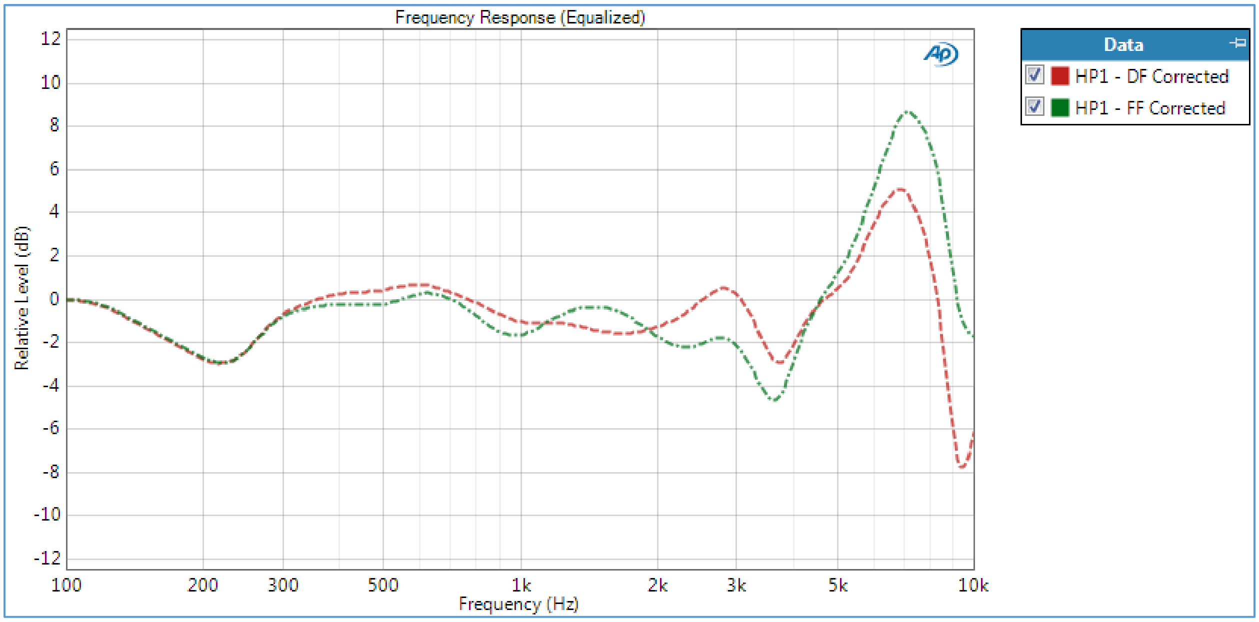

Figure 9. Frequency response of Headphone 1 (as measured in Figure 8) corrected with Diffuse Field and Free Field equalization.

Frequency Response Measurement on an Acoustic Test Fixture

This is one of the main methods of measuring the frequency response of headphones specified in IEC 60268-7, where it is referred to as "coupler or ear simulator (including HATS) frequency response"[9]. It is defined as the variation of sound pressure level in the ear simulator as a function of frequency when a sinusoidal voltage is applied to the headphone. In addition to sinusoidal signals, the standard allows for frequency response to be deduced from measurements using noise signals or impulses. However, if a non-sinusoidal signal is used, it is the responsibility of the tester to demonstrate that test results are equivalent to sine-based methods.

A technique for measuring frequency response based on the Farina log-swept sine chirp stimulus [11] was introduced in 2000, and since that time the technique has become the preferred method for measuring frequency response of audio devices, including loudspeakers and headphones. This method uses a sine stimulus that varies continuously over the desired frequency range in a very short time (from tenths of a second to a few seconds). Measurements are very fast and have the added benefits that harmonic distortion and even rub and buzz distortion can be measured at the same time as acoustic frequency response. The same technique can be used to measure impedance versus frequency. The frequency response measurements shown in this document were all made using the log-swept sine chirp method.

Frequency Response—Alternative Measurement Methods

In addition to measurements on an acoustic test fixture, standard IEC 60268-7 provides several alternative methods to evaluate the frequency response of headphones or earphones, all of which involve the use of human subjects and a free or diffuse sound field. Two of these methods are subjective: Subjects listen to band limited noise signals presented alternately in the headphones and in a (free or diffuse) sound field using their open ears, and then adjust the level of the headphone signal until equal perceived loudness is achieved. Two other methods involve comparison of sound levels measured with a small probe microphone inside the ear canal of human subjects when listening to the same band limited noise signals through headphones and through open

[9] IEC 60268-7 states, "*Coupler or ear simulator measurements, purely objective, are relatively simple and repeatability is sufficient. They are, therefore, most useful for production testing, quality control and commercial specifications.*"

ears in a (free or diffuse) sound field. These field comparison methods involving human subjects are much more complicated and time consuming than measurements on an ATF, because multiple subjects are required and the frequency response must be measured in 1/3-octave frequency bands, one band at a time.

According to IEC 60268-7, the reason for having two categories of frequency response measurements (ATF and sound field comparison) is that "*…no method has yet been developed that is universally applicable.*" Another note in the standard states, "*No known objective method produces a flat frequency response characteristic from an earphone which is subjectively judged to produce wide band uncolored reproduction.*" This explains the lack of an Effective Frequency Range characteristic in IEC 60268-7 (headphones and earphones) as compared to IEC 60268-5 (loudspeakers), for which there is general consensus that a flat frequency response is preferred.

Headphone Measurement Procedures

Rated Source Impedance

For most of the measurements described in IEC 60268-7 (including frequency response), the standard requires that the test signal be applied to the headphones in series with the manufacturer's "rated source impedance." This is one of several "rated conditions" like application force and working temperature range that are supposed to be taken from the manufacturer's specification sheet. However, based on a review of several headphone data sheets, it appears that most headphone manufacturers do not specify a rated source impedance. The standard includes the following note on this subject: *"The performance of headphones depends very little on the source impedance. However, in order to allow headphones of widely different impedances to be reasonably well matched, in terms of the sound pressure level produced, to a single headphone output on other equipment, IEC 61938 at present specifies a source impedance of 120 Ω, intermediate between the lowest and highest likely impedances of available headphones. It is thus important for the manufacturer to specify the rated source impedance, particularly if, for some reason, it is not 120 Ω.*"

To help qualify the statement that performance depends little on source impedance, we measured the frequency response of Headphone 1 referred to in Figure 8 in series with source impedances varying from 20 to 200 Ω. These results are shown in Figure 10. The curve labeled "None" in Figure 10 pertains to a measurement in which no additional resistance was added to the internal source impedance of the power amplifier (about 0.1 Ω in this case). This headphone has a nominal impedance of 63 Ω.

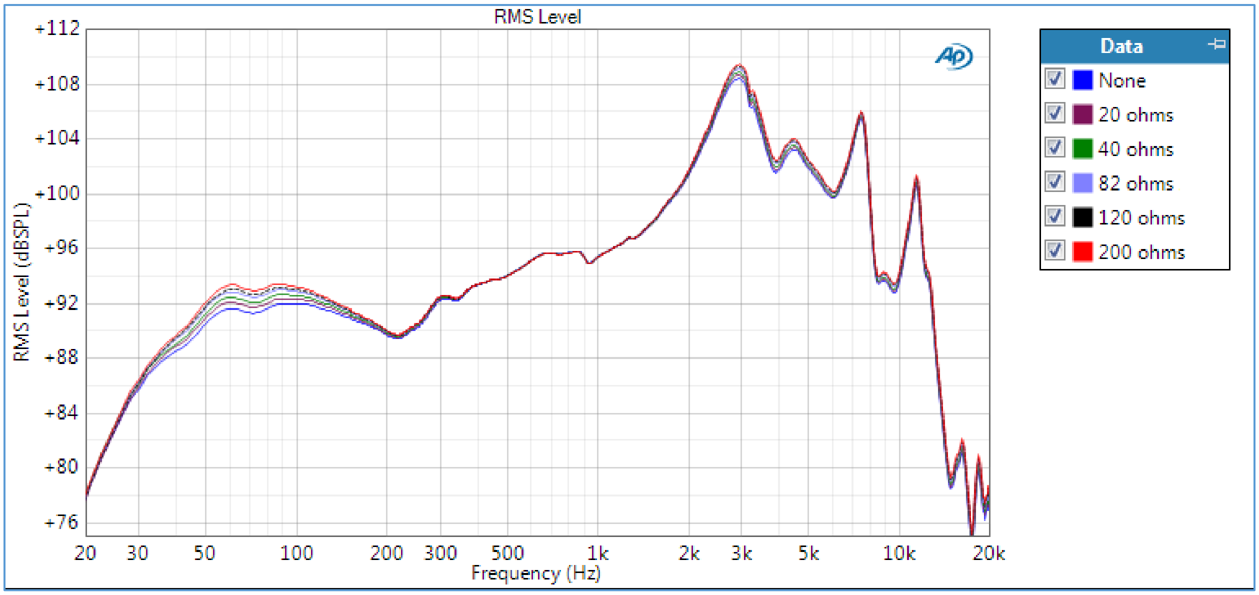

Figure 10. Frequency response of Headphone 1 as measured with various source impedances at the characteristic voltage. The maximum variation of about 1.7 dB between curves occurs at approximately 60 Hz.

Concerning source impedance, regardless of its effect on headphone performance, testers should be careful to check and record the source impedance of the amplifier used for headphone measurements. An instrumentation quality power amplifier has a source impedance of less than 0.1 Ω and a high quality DAC with a headphone jack that we tested had a source impedance of 0.8 Ω. AV receivers are less predictable in this regard. The headphone jack of one recent “surround sound” receiver that we tested had a source impedance of 1.3 kΩ.

Standard Measurement Conditions

Most of the electroacoustic measurements specified in IEC 60268-7 require that the headphones be “brought under standard conditions for measurement” before conducting the measurement. These standard measurement conditions include:

1. The earphone(s) should be applied to the ear simulator(s) with the manufacturer’s rated application force.
2. A 500 Hz sinusoidal voltage is applied in series with the rated source impedance such that a sound pressure level of 94 dBSPL is measured in the ear simulator. (Note: This voltage as measured at the headphone input is also known as the characteristic voltage.)
3. Volume controls, if present should be set at minimum attenuation. For headphones which use a preamplifier and for wireless headphones, the manufacturer should specify a reference gain setting for measurements.
4. Balance controls, if present, should be set for equal balance.
5. Crosstalk controls, if present, should be set for minimum crosstalk.
6. If the headphone requires a power supply, it should be set for the rated voltage and frequency.

Ear Simulator Calibration

The ear simulators of an ATF contain microphones that produce a voltage proportional to the sound pressure at the Drum Reference Point. Typically, each microphone has a sensitivity that is slightly different from a specified nominal value. In most cases, users will want to "calibrate" these inputs to an audio analyzer such that the analyzer displays results for both channels scaled in pressure units of Pascal (Pa) and dBSPL (decibels relative to 20 µPa). This is not a true calibration, but rather the practice of assigning the sensitivity of each ear simulator in V/Pa to the corresponding input channel. Although microphone sensitivities can be read from the calibration data sheet supplied with the ear simulators, it is a good practice to use a sound level calibrator or a pistonphone to set or verify these values. These devices produce a sinusoidal signal with a known sound pressure level, typically 114 dBSPL at 250 Hz, when properly coupled to an ear simulator. An adaptor is used to fit the calibrator over the ear canal extension of the ear simulator as shown in Figure 11. Note: A sound level calibrator or a pistonphone with a nominal sine frequency of 250 Hz should be used for this purpose, because the frequency response of the ear simulator is still flat at this frequency. Using a calibrator with a sine frequency of 1,000 Hz would require compensating for the acoustic gain of the ear simulator at this frequency.

Figure 11. Using a CAL250 sound level calibrator to calibrate a test fixture's ear simulator microphone.

The Importance of Fit

The fit of an earphone to the head and/or pinna can have a dramatic effect on performance. This is especially true for the bass response of closed headphones; leaks of any sort will reduce the ability of the earphone to generate sound at low frequencies. For example, Figure 11 shows five frequency response measurement of Headphone 1 (introduced in Figure 8). In this case, the headphones were removed from the ATF and then reapplied before each measurement. To account for this variation with fit, it is a good practice to average the results of several measurements (typically 3 to 5) with the headphones being removed and re-applied between measurements.

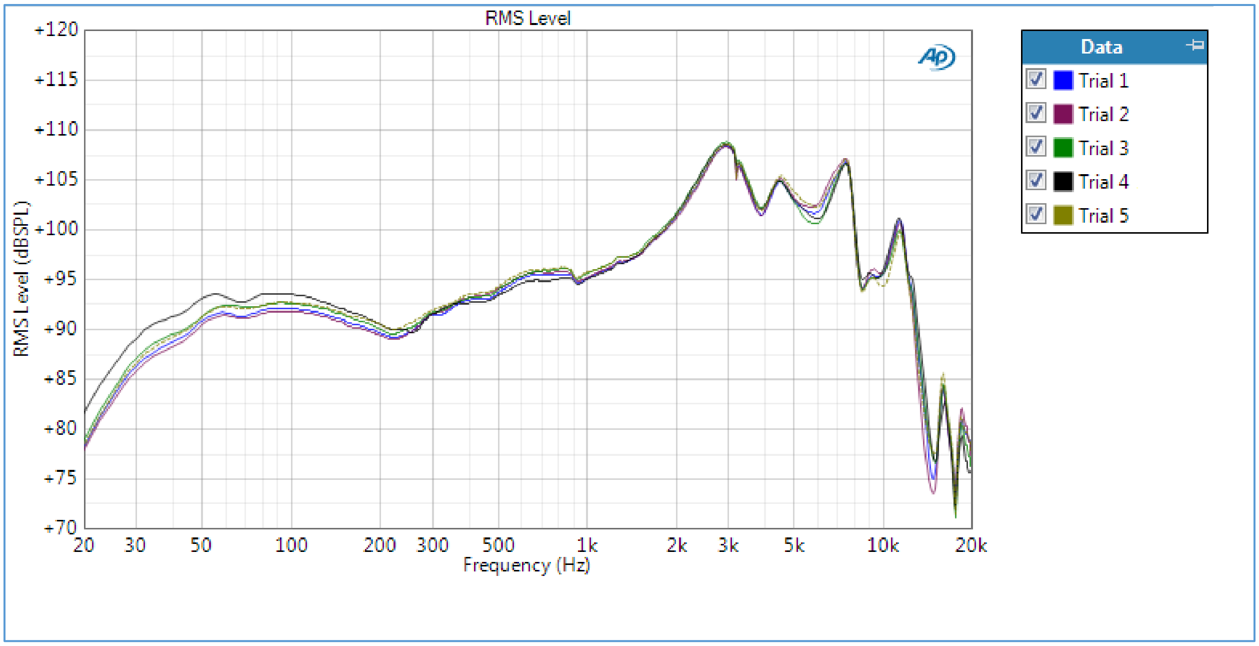

Figure 11. Frequency response of circumaural Headphone 1 for 5 cycles of placing the headphones on the ATF.

A similar measurement to Figure 11 for an insert type earphone (referred to as Earphone 1) is shown in Figure 12. In this case, the variation due to fit is most noticeable at high frequencies (above 6 kHz), probably due to slightly different insertion depths with each trial, which changes the resonant frequency of the closed ear canal. Note the extended bass response of the insert earphone, likely due to the fact that it completely seals the opening of ear canal.

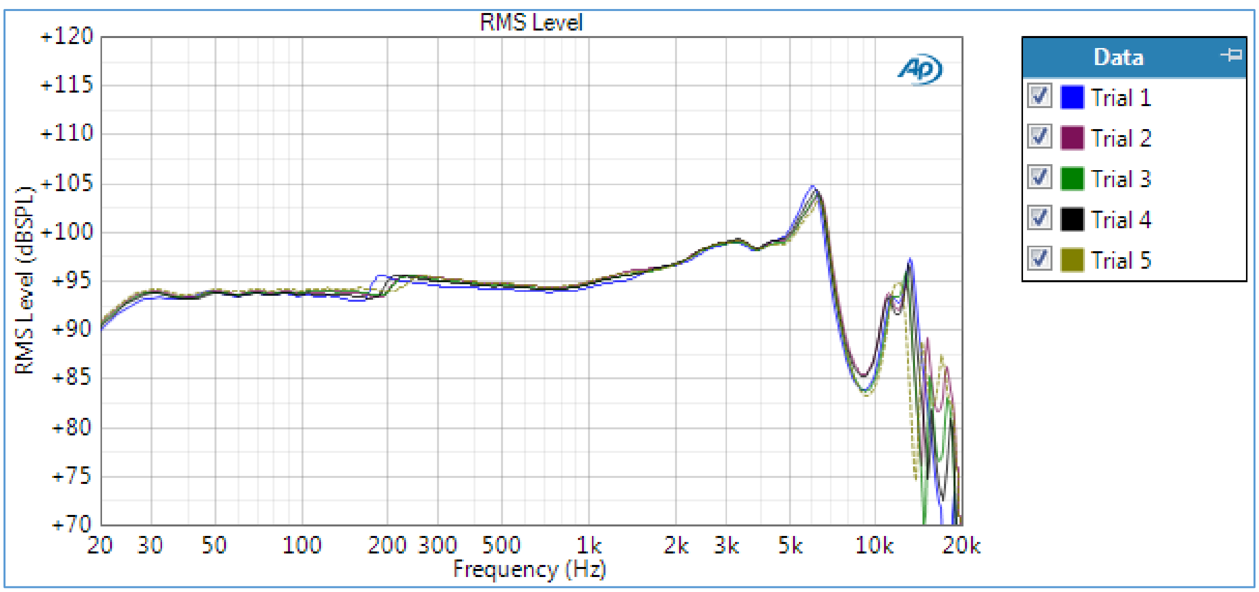

Figure 12. Frequency response of an insert Earphone 1 for 5 cycles of placing the earphone on the ATF.

Left/Right Tracking

Although not specified in IEC 60268-7, Left/Right Tracking is a useful metric for stereo headphones, because it measures the relative response of each earphone in a pair of headphones. It is easily derived from frequency response measurements on an ATF with two ear simulators by comparing the response from the right and left ear. Earphones that match perfectly will have a Left/Right Tracking response curve that is a flat line at 0 dB. As shown in Figure 13, the left and right earphones of insert Earphone 1 are well matched from 20 Hz to 10 kHz.

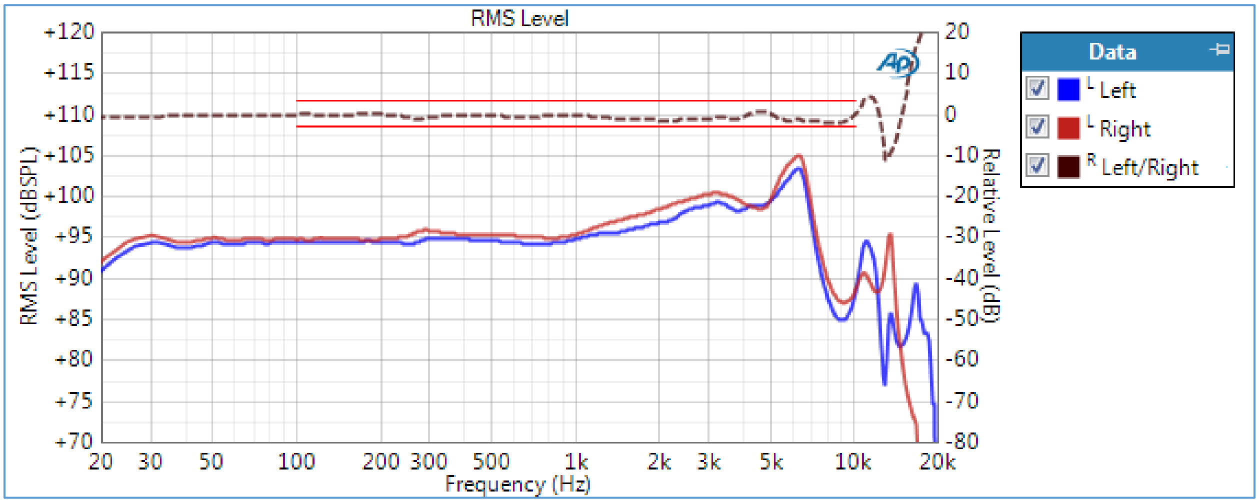

Figure 13. Frequency response of the left and right earphones of Insert Earphone 1 (left axis) and their Left/Right tracking response curve with ± 3 dB limits (right axis).

Crosstalk

Crosstalk Attenuation is covered in section 8.12 of IEC 60268-7, but it is really a special type of frequency response measurement. It is most convenient to measure it at the same time as frequency response and Left/Right Tracking. To measure Right-into-Left crosstalk, simply measure the response in the Left ear simulator when the left earphone is driven and the right is not driven. Then repeat the measurement with the right channel driven and the left channel not driven. The ratio of these two curves is the Right-into-Left crosstalk.

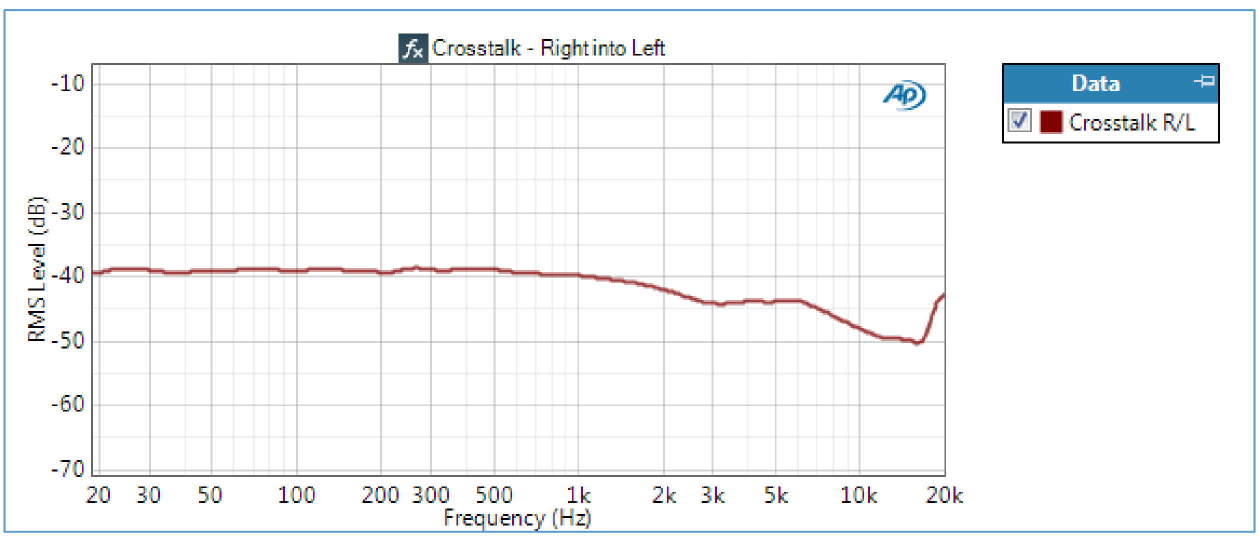

Figure 14. Measured crosstalk (right into left) of insert Earphone 1

Ambient Noise Considerations

When making acoustic measurements, a test environment with low ambient noise levels is highly desirable for measurement results that are free of noise contamination. This is especially true for distortion measurements, in which distortion signal components are (ideally) orders of magnitude lower than the stimulus signal. If the ambient noise in the test environment is too high, this noise can be interpreted by measurement algorithms as distortion.

It is a good practice to measure the ambient noise when making acoustic measurements. One easy way to get an estimate of the ambient noise spectrum while measuring frequency response is to conduct a measurement with the generator switched off. Figure 15 shows a set of frequency response measurements of a headphone at three signal levels: one at the characteristic voltage, V_{ch} (the voltage which results in 94 dBSPL at 500 Hz), one at V_{ch} −6 dB[10], and one with the generator switched off (labeled Noise). These measurements were conducted in a typical office environment at a time when no other workers were present. The various peaks in the noise spectrum are due to noise from the building's Heating, Ventilating and Air Conditioning (HVAC) system and a nearby computer cooling fan. Even though this measurement appears to have a relatively high signal-to-noise ratio, the noise level at some frequencies is close to being excessive for good distortion measurements. For example, keep in mind that the noise peak at 580 Hz will affect the calculated Total Harmonic Distortion (THD) Ratio estimate at sub-multiples of this frequency (290 Hz, 193 Hz, …, etc.). For critical measurements, a room or chamber with good noise isolation is required.

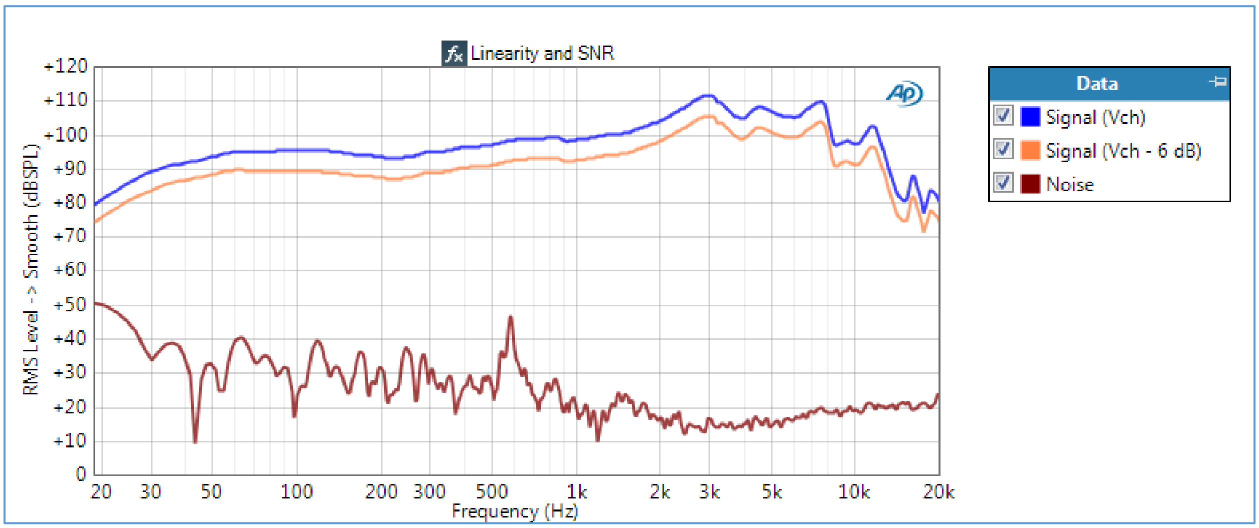

Figure 15. Headphone 1 frequency response measurement at 3 signal levels" V_{ch}, V_{ch} - 6 dB and no signal.

Electrical Impedance

Electrical impedance is important for matching headphones with power amplifiers. IEC 60268-7 requires that headphones have a Rated Impedance. This nominal impedance is the value of a pure resistance specified by the manufacturer for matching purposes. The standard requires that the headphone's measured impedance magnitude versus frequency curve must not be less than 80% of the rated value at any frequency within the rated frequency range.

To derive impedance, one must measure the voltage input to the headphone and the current in the circuit as a function of frequency. Typically, a logarithmically swept sine signal is used from 20 Hz to 20 kHz. To measure current, a "sense resistor" is typically used. This is a small (e.g., 1.0 or 0.1 Ω) precision resistor placed in series with the headphone. The voltage drop across the sense resistor is used to calculate the current.

[10] The measurement at V_{ch} −6 dB will be used later to estimate the linearity of the Device Under Test (DUT)

Impedance should be measured at a constant drive level that is low enough to ensure that the headphone operates in a linear region. This can easily be tested by measuring the acoustic frequency response at two levels a few decibels apart. For example, the curves V_{ch} −6 dB and V_{ch} of Figure 15 were compared by taking their difference in dBSPL (their ratio in Pa) and the resulting comparison curve was normalized to 1 kHz. This result is shown in Figure 16. For a perfectly linear system, the result should be a flat line at 0 dB.

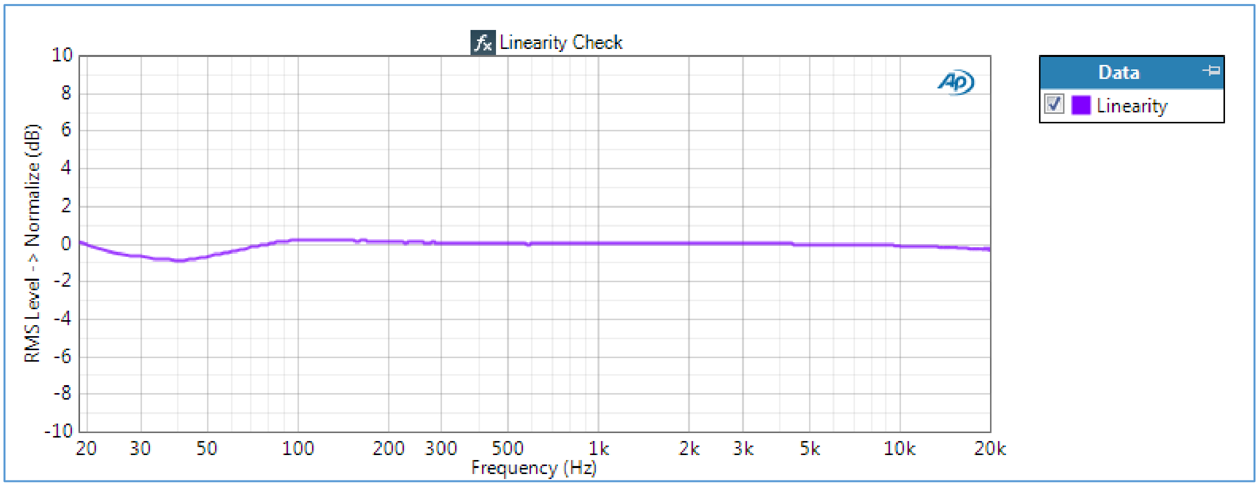

Figure 16. Linearity check— the Level responses of Headphone 1 at two drive levels 6 dB apart are compared in the frequency domain.

Since voltage and current are each phasor or complex quantities, having both magnitude and phase (or real and imaginary parts), impedance is also. However, only the impedance magnitude curve is considered when evaluating the rated impedance. Figure 17 shows measured impedance curves for Headphone 1 (introduced in Figure 1Figure 8) with a line indicating the value at 80% of the headphone's nominal rated impedance of 63 Ω. The impedance measurement is one of the measurements in IEC 60268-7 requiring standard measurement conditions, which means that the test must be conducted on an acoustic test fixture. The free air measurement in Figure 17 was included to illustrate the effect of the acoustic loading on the measured impedance magnitude curve.

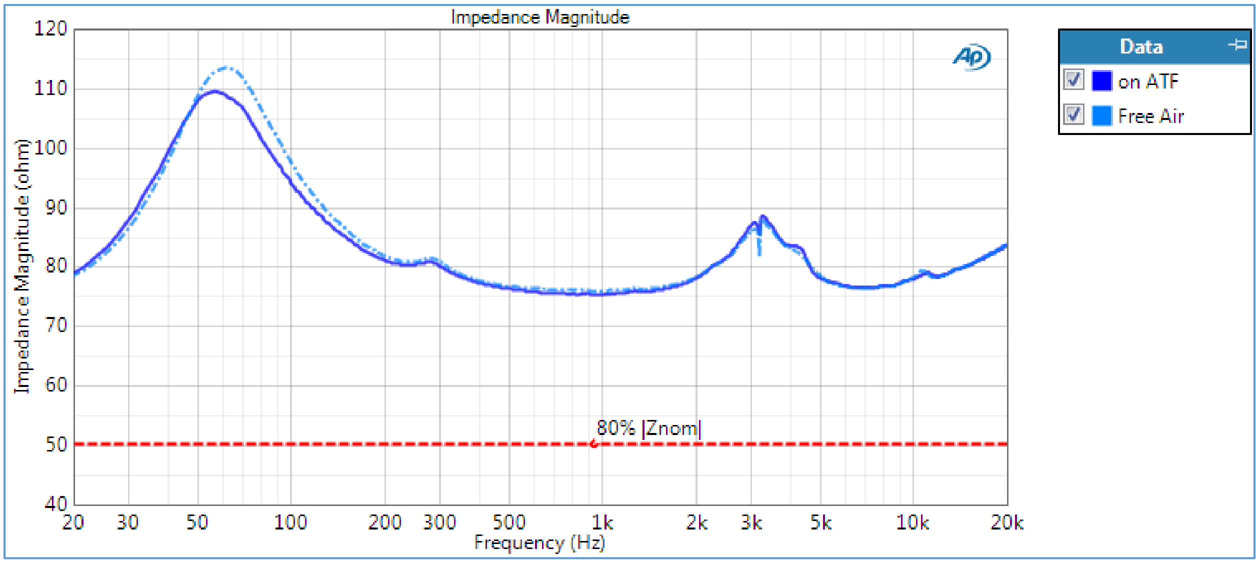

Figure 17. Impedance magnitude curves measured on an ATF and in free air for Headphone 1 (introduced in Figure 8). The horizontal dashed line indicates the value at 80% of the nominal impedance.

Input Voltages

Input voltages are important because they specify the voltages with which headphones are intended to work.

The Program Simulation Signal

IEC 60268-7 specifies several input characteristic voltages for headphones, many of which are based on a special noise signal called the Program Simulation signal. The signal is created by filtering pink noise with a special bandpass filter that has the gain response shown in Figure 18. It is meant to be representative of the long-term average spectrum of program material (music and speech). Part 7 of the standard also requires a variant of the signal that has a specific crest factor within the range of 1.8 to 2.2.[11]

[11] Both variations of the Program Simulation signal are available as standard waveform types in Audio Precision APx500 Series audio analyzers.

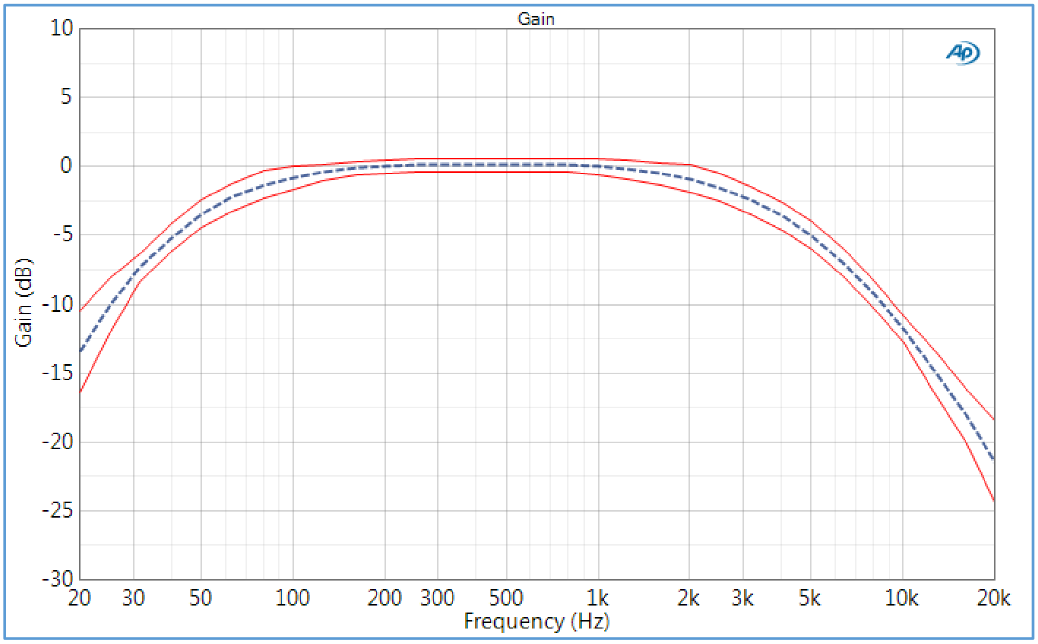

Figure 18. Power spectrum of the Program Simulation Noise signal per IEC 60268-1 (blue) with limits (red).

The input voltage characteristics specified in IEC 60268-7 include:

1. Rated source e.m.f.: The manufacturer's specified maximum rms voltage that should be applied to the headphone through the rated source impedance during the reproduction of normal program signals.
2. Rated long-term maximum source e.m.f.: The maximum voltage which the headphone can tolerate without permanent damage, for 10 cycles of 1 minute of signal application followed by 2 minutes rest, using the crest factor limited version of the program simulation signal.
3. Rated maximum permanent noise source e.m.f.: Similar to item 2, above except that the signal is applied for a continuous period of 100 hours.
4. Characteristic voltage: The voltage at which a 500 Hz sine signal applied through the rated source impedance produces a sound pressure level of 94 dBSPL in the ear simulator.
5. Simulated program signal characteristic voltage: The voltage at which the simulated program signal applied through the rated source impedance produces a sound pressure level of 94 dBSPL in the ear simulator.
6. Simulated program signal characteristic voltage corrected by A-weighting and free-field response compensation: The same as item 5, above, except that the sound pressure level measured in the ear simulator is A-weighted and corrected to the free field.

These input voltage characteristics are easily measured using an audio analyzer, which includes features such as the IEC 60268-1 Program Simulation noise signal (with and without reduced crest factor), the ability to regulate the signal generator to a specified level, measurement of long-term rms levels, frequency weighting filters and a feature known as Input EQ to correct the response measured in an ear simulator to the free field.

Note: IEC 60268-7 also specifies input power characteristics corresponding to the specified input voltage characteristics. These can be derived from the voltage characteristics using the nominal rated headphone impedance.

Sound Pressure Level

The sound pressure level (SPL) section of IEC 60268-7 specifies methods to determine what sound pressure levels the headphones will generate when the input voltages from the previous section are applied. The specified characteristics are:

1. Maximum SPL: The sound pressure level produced in the ear simulator when the headphone is driven with a 500 Hz sinusoidal voltage at the source e.m.f., in series with the rated source impedance.
2. Working SPL: The sound pressure level produced in the ear simulator when the headphone is driven with a 500 Hz sinusoidal voltage in series with the rated source impedance at a level equivalent to 1 mW into the headphone's nominal rated impedance.
3. Simulated program signal working SPL: Similar to item 2, immediately above, except that the program simulation signal is used instead of a 500 Hz sinusoid.
4. Simulated program signal working SPL corrected by A-weighting and free-field response compensation: Similar to item 3, immediately above, except that the sound pressure level measured in the ear simulator is A-weighted and corrected to the free field.

Headphone 1, introduced in Figure 8, has a nominal impedance of 63 ohms. The voltage corresponding to 1 mW into this load is 251 mV. This headphone had a measured working sound pressure level of 94.9 dBSPL. In this case the input power at the characteristic voltage (226 mV) was very close to 1 mW.

It is easy to determine the simulated program signal working SPLs with an audio analyzer. For the version measured directly in the ear simulator (item 3, above), the rms input voltage to the headphone should be measured for a relatively long integration period (10 seconds or more). Based on this measured value, the generator level can be adjusted as required to achieve the target level of 1 mW. Once the target is reached, the analyzer can be used to measure the rms level in the ear simulator. For the A-weighted and free field corrected version, the procedure is the same, except an A-weighting filter and an EQ curve corresponding to the inverse of the free field to DRP HRTF (Figure 2) are inserted at the input. For Headphone 1, the simulated program signal working SPL was measured at 99.7 dBSPL and the A-weighted and free field corrected working SPL was measured at 89.7 dBA.

Figure 19 shows long term 1/24-octave SPL spectra measured in the ear simulator of an ATF for Headphone 1 driven with the program simulation noise signal. Three spectra are shown: unweighted (DRP), free field corrected and free field corrected with A-weighting. Note that the unweighted curve closely resembles the free field HRTF, as it should, because the stimulus is broadband noise.

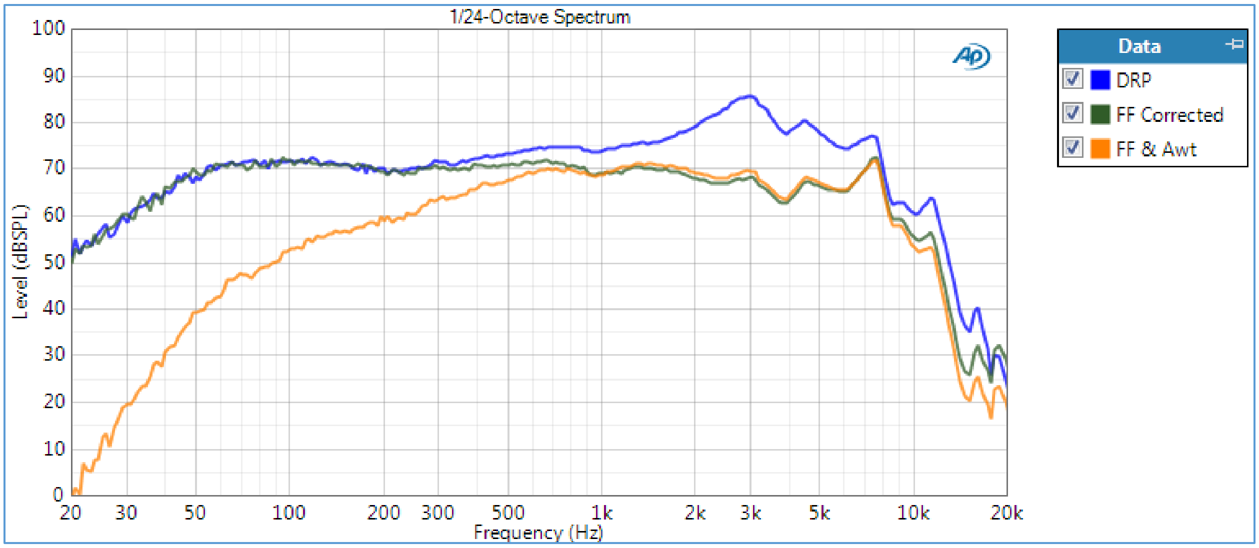

Figure 19. 1/24th octave spectra of the subject headphone when driven with the IEC 60268-1 program simulation signal at 1 mW—(a) as measured at the Drum Reference Point, (b) corrected to the free field, and (c) free field corrected and A-weighted.

A related European standard (BS EN50332) covers methods for measuring the maximum sound pressure level of headphones and earphones used with portable media players with a view to limiting noise induced hearing loss [14], [15].

Distortion

IEC 60268-7 covers distortion in section 8.7, titled Amplitude Non-linearity. Harmonic distortion and two types of intermodulation distortion are specified.

Harmonic Distortion

As mentioned previously, one of the advantages of the log-swept sine chirp method of measuring frequency response is that harmonic distortion can be measured with acoustic response simultaneously. IEC 60268-7 requires that only 2nd and 3rd order harmonic distortion be specified and measured. Figure 20 shows a level and distortion plot for insert Earphone 1 introduced in Figure 12. This plot shows the levels of distortion products of the 2nd and 3rd harmonics (H2 and H3) and the total harmonic distortion. The total harmonic distortion level is approximately 40 dB below the fundamental signal level from about 20 Hz to 3 kHz, resulting in a THD Ratio of −40 dB or about 1% (Figure 21).

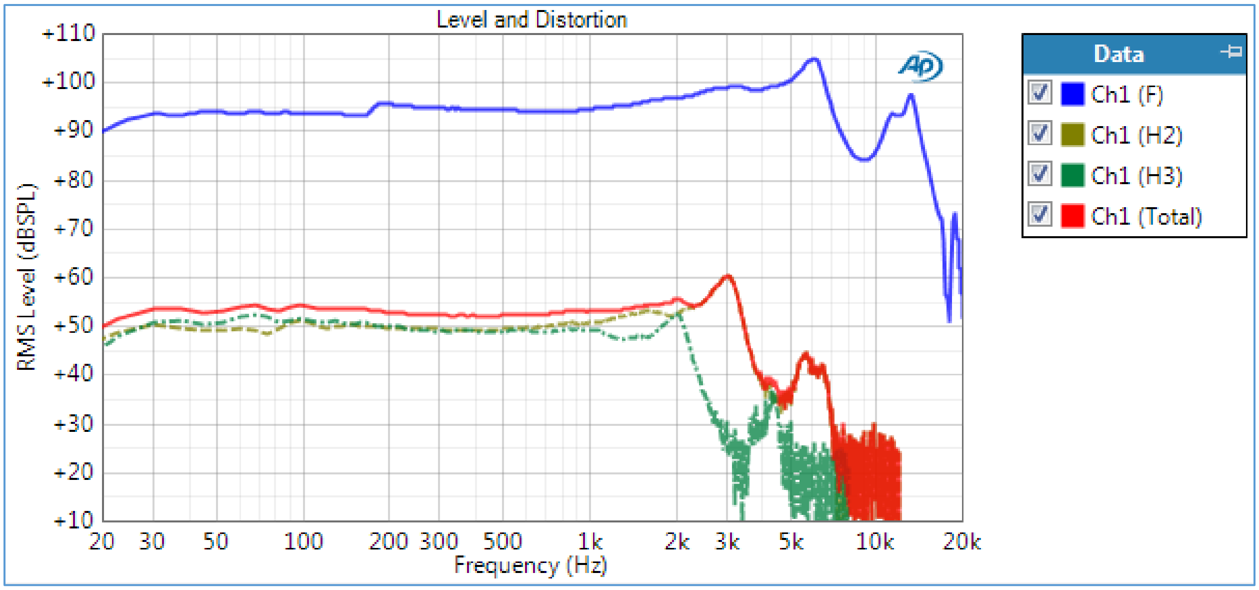

Figure 20. Level and distortion plot for insert Earphone 1 tested at the characteristic voltage of an ATF with pinna and ear canal extension.

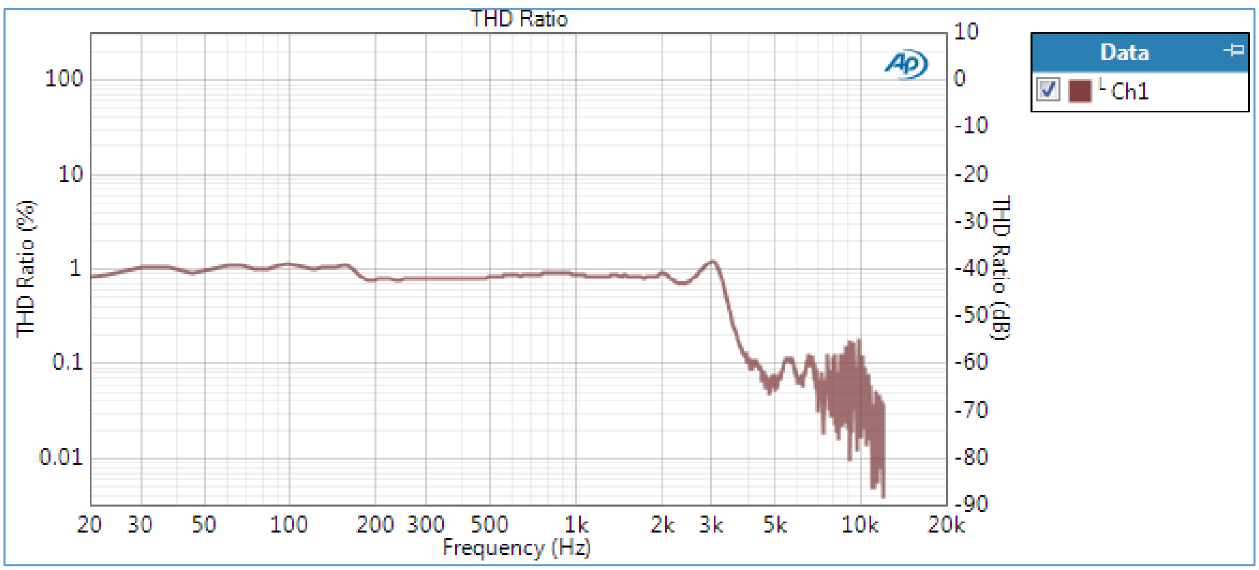

Figure 21. Total Harmonic Distortion Ratio response of insert Earphone 1 from the same measurement as Figure 20.

Modulation Distortion

Section 8.7.3 of IEC 60268-7 covers Modulation Distortion, one of the two types of intermodulation distortion specified. In this case, the specified characteristic is the 2nd and 3rd order intermodulation distortion ratios when the signal is composed of two sinusoids—one at 70 Hz and the other at 600 Hz—with amplitude ratio of 4:1. The signal levels of the two sinusoids should be −1.9 dB and −4.0 dB respectively, relative to the rated input voltage. The 2nd order modulation distortion ratio is calculated from the sum of the 2nd order IMD products at 530 Hz and 670 Hz, expressed as a ratio to the level of the 600 Hz sine component. The third order modulation distortion is similarly calculated from the 3rd order products at 460 Hz and 740 Hz.

Figure 22 shows the FFT spectrum of insert Earphone 1 when driven with the required signal. For clarity, the spectrum is plotted in units of dB relative to the level of the 600 Hz sine component. For this measurement, the 2nd and 3rd order modulation distortion ratios were −36.3 and −32.1 dB, respectively.

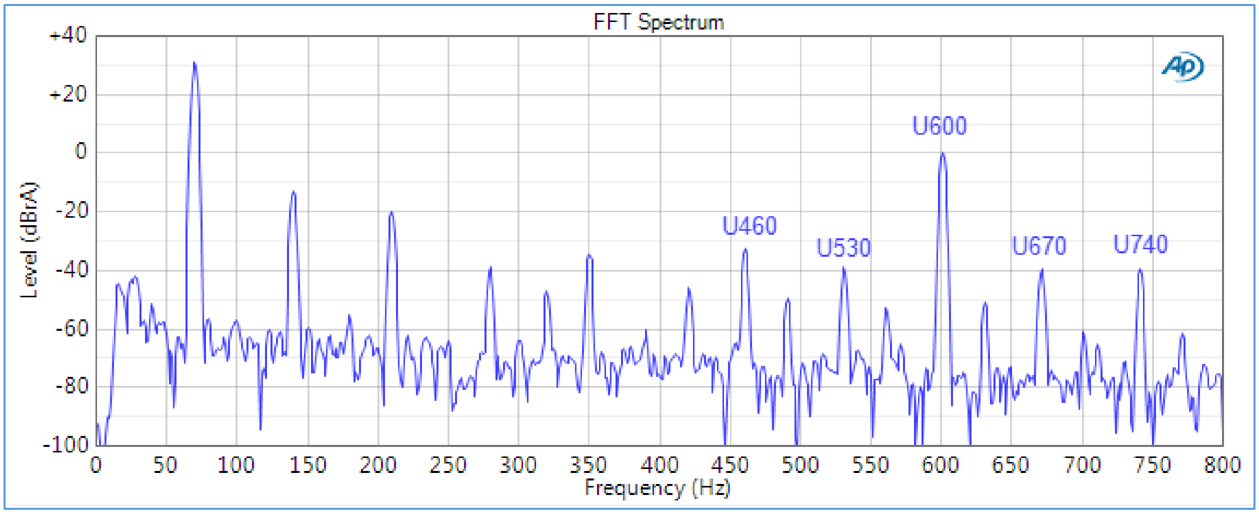

Figure 22. FFT spectrum of insert Earphone 1 subjected to the Modulation distortion signal at 70 Hz and 600 Hz. Second and third order intermodulation distortion components are also noted.

Difference Frequency Distortion

Difference Frequency Distortion (DFD) is the second type of intermodulation distortion specified in IEC 60268-7. This measurement uses two sinusoidal signals, separated in frequency by 80 Hz, with each having one half the rated input voltage. The distortion products are expressed as a ratio of the overall signal level. The sine frequencies can be swept to create a DFD spectrum. Figure 23 shows a DFD spectrum in which the mean frequency was swept from 250 Hz to 20 kHz.

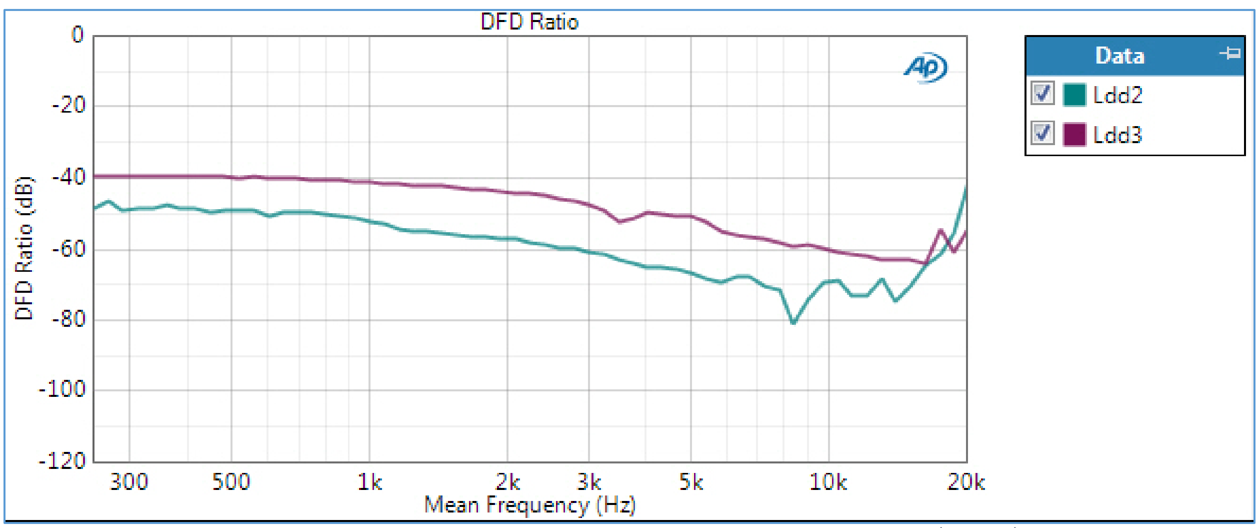

Figure 23. Difference Frequency Distortion sweep of insert Earphone 1. Ldd2 and Ldd3 are the 2nd and 3rd order distortion products, respectively.

IMD measurements are particularly useful in bandwidth limited systems because some distortion products occur at frequencies lower than the stimulus frequency. In such systems, harmonic distortion components quickly exceed the measurement bandwidth as the frequency of the fundamental signal is increased.

Rub and Buzz Distortion

Rub and buzz is a type of distortion which is not addressed in IEC 60268-7, but is of interest to headphone manufacturers, particularly as a production test measurement. Rub and buzz defects can often be difficult to detect using classic distortion measurements. Audio Precision APx500 audio analyzers have an optional rub and buzz detection algorithm which works with the log-swept sine chirp frequency response measurement. It is based on the fact that rubs and buzzes typically result in higher frequency signals that are "spiky" in nature (i.e. they have a high crest factor). One of the metrics it uses is called the Rub and Buzz Crest Factor. It is derived by calculating the crest factor of the signal after high-pass filtering it at a frequency typically 10 to 20 times higher than the fundamental frequency. The algorithm can be "trained" by setting limits based on known good devices. However, experience shows that drivers without defects typically have a Rub and Buzz Crest Factor lower than about 13 dB.

Figure 24 shows the Rub and Buzz Crest Factor measured on a set of Bluetooth noise canceling headphones. As shown, the left earphone had a crest factor well over 13 dB in the frequency range from about 25 Hz to 125 Hz. Prior to conducting this test, no issues were noted for these headphones when listening to music. Subsequently, however, when they were driven with a sine signal in the 25 Hz to 125 Hz range, a buzz defect was clearly audible in the left earphone.

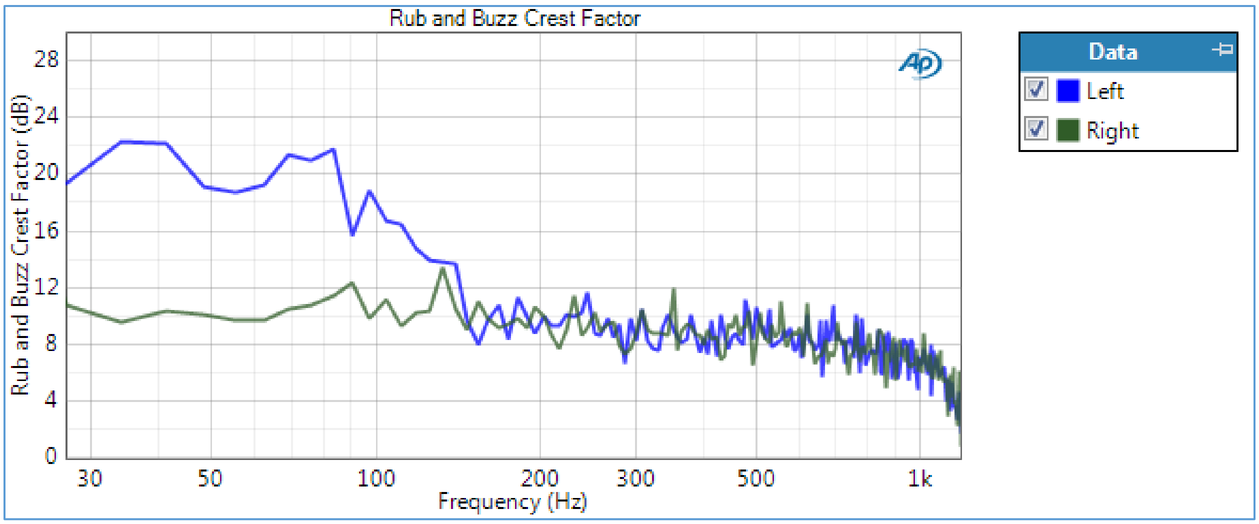

Figure 24. Rub and Buzz Crest Factor measured on a pair of noise canceling Bluetooth headphones. The Left earphone had a very audible buzz when driven with a sine signal in the frequency range from 25 to 125 Hz.

Sound Attenuation

Sound attenuation is a measure of how effective a headphone or earphone is at blocking ambient noise from entering the ear canal. This is of particular interest to manufacturers of headphones equipped with active noise cancellation (ANC). IEC 60268-7 specifies that sound attenuation measurements shall be made according to ISO 4869-1 [16], a standard for hearing protectors. It makes brief mention of ANC headphones, but only to state that they may "require a modified procedure."

ISO 4869-1 is a subjective measurement method, based on measuring the hearing threshold of 16 human subjects with and without hearing protectors in place. While this is likely the most accurate method of measuring headphone sound attenuation, such measurements are difficult and time consuming. A more convenient method, which lends itself well to ANC headphones, is based on ISO 4869-3 [17–19] and the use of an acoustic test fixture.

ISO standard 4869-3 requires creating either a random incidence sound field around the ATF or a plane progressive wave sound field. It includes detailed requirements for each type of sound field and measurements to verify that the sound field complies with the requirements. A broad band signal such as pink noise is generated and sound levels in the ear simulators[12] of the ATF are measured in 1/3-octave bands. For headphones without ANC, the procedure requires first measuring the 1/3-octave sound level spectrum of the open ear (headphones removed), and then repeating the measurement with the headphones in place. The insertion loss is calculated as the difference between these spectra. For headphones with ANC, an additional step is required: measurements are conducted with and without the ANC feature enabled, from which passive and active attenuation values are calculated. Measured spectra are typically normalized to the measured open ear spectrum, as shown in Figure 25. This graph indicates that the active noise attenuation is effective below about 1.5 kHz, and that it is less effective than passive attenuation alone in the frequency range from about 1.5 kHz to 4 kHz.

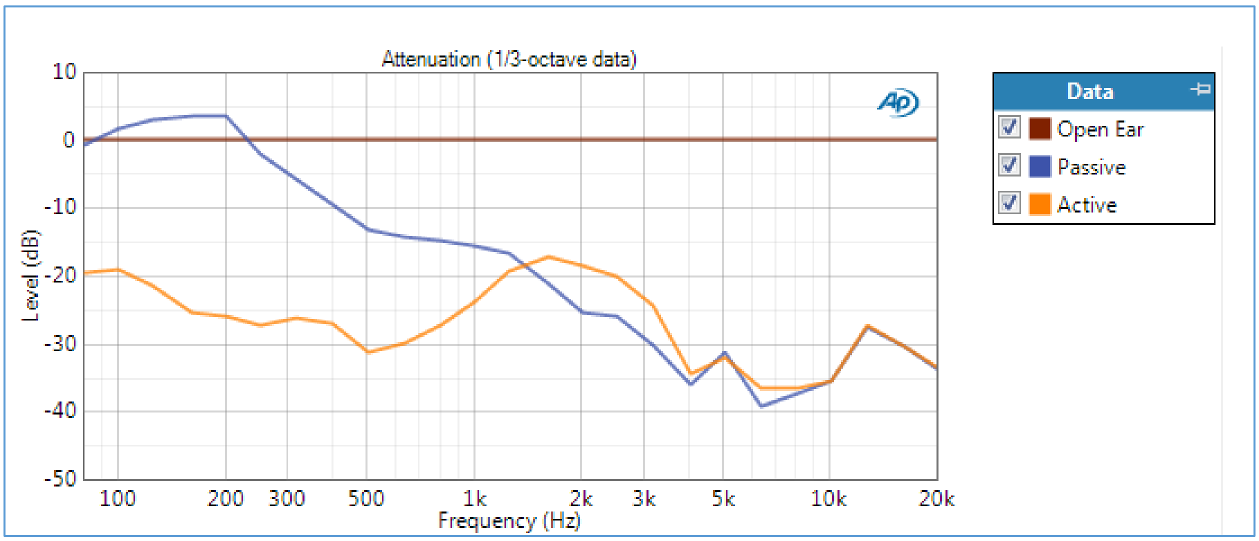

Figure 25. Normalized spectra from one measurement of an ANC headphone showing passive and active attenuation.

[12] Because ISO 4869-3 is only measuring insertion loss of headphones, it does not require occluded ear simulators. However, an ATF with ear simulators can also be used for this purpose.

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