The "0-Ohm" Headphone Amplifier

The Sonic Advantages of Low-Impedance Headphone Amplifiers

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The circuits used to drive headphones are often added to a product without careful consideration of the difficult loads presented by high-quality headphones. The most common circuit is an opamp driver followed by a 30-Ohm series resistor. The series resistor provides short-circuit and overload protection while isolating the opamp from the inductance and capacitance of the headphones. The series resistor protects the opamp while keeping it stable. In contrast, today's state-of-the-art headphone amplifiers eliminate the series resistor, and use a high current driver. This change reduces distortion and flattens the frequency response when a headphone is driven. These new high-end designs are often called "0-Ohm" headphone amplifiers, and are essentially miniature power amplifiers. This paper provides measurements which demonstrate the significant advantages of headphone amplifiers with very low (near 0-Ohm) output impedances. A low output impedance increases the damping factor of the amplifier-headphone system. This paper will show that a high damping factor reduces distortion at the headphone inputs, improves phase response, and flattens frequency response.

Damping factor has long been recognized as an important parameter for audio power amplifiers, but has been ignored when building and testing headphone amplifiers. An amplifier has improved control over the physical movements of transducers when the damping factor is high. This control is essential for reducing the distortion caused by mechanical resonances in the transducers. A high damping factor also improves time-domain response by quickly accelerating and damping the mechanical motions of the transducers in response to musical transients. Finally, a high damping factor insures that transducer impedance vs. frequency variations have minimal effect on frequency and phase response. Damping factor is simply the ratio of the load impedance to the source impedance.

$$Damping\ Factor = \frac{Load\ Impedance}{Amplifier\ Output\ Impedance}$$

An amplifier with a high output impedance will have a poor damping factor. For example, a traditional headphone amplifier with a 30-Ohm output impedance has a damping factor of only 2 when driving 60-Ohm headphones. In contrast, Benchmark's "0-Ohm" HPA2™ headphone amplifier (incorporated into many Benchmark products) has an output impedance of approximately 0.01 Ohms. This means that the HPA2™ has a damping factor of approximately 6,000 when driving 60-Ohm headphones. The following tests show how a high damping factor improves audio performance.

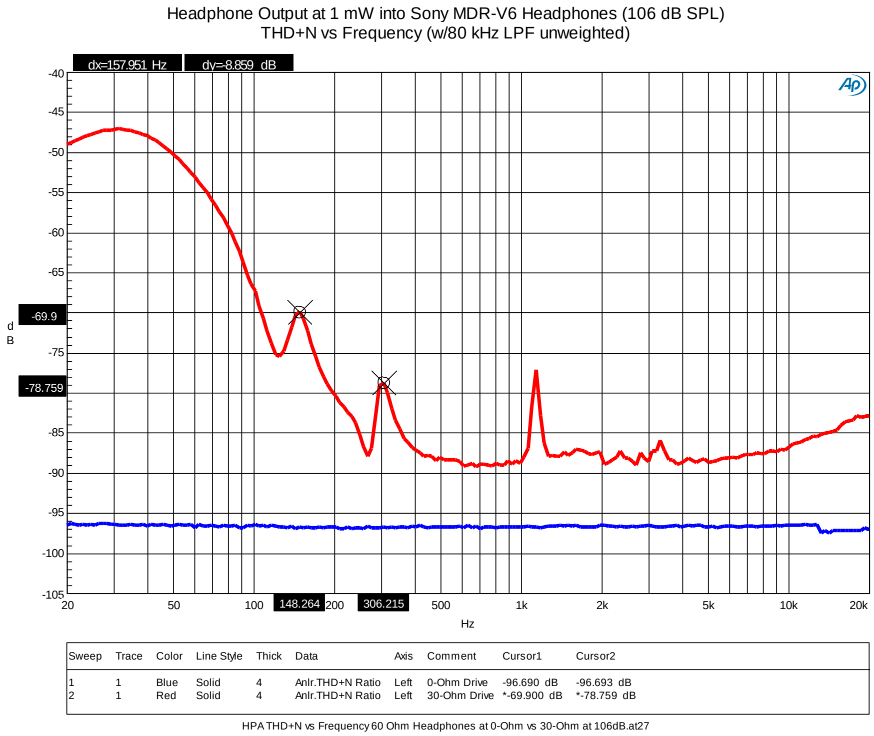


Figure 1 demonstrates dramatic differences in distortion as the damping factor is changed while driving headphones. The plot shows THD+N vs. frequency. The blue trace shows minimal distortion at a damping factor of about 6,000. The red trace shows significant distortion at a damping factor of about 2. The two traces show a 50 dB difference in low-frequency distortion. The red trace also shows evidence of transducer resonance problems near 150 Hz, 300 Hz, and 1.2 kHz.

The blue trace in Figure 1 was produced using a Benchmark HPA2™ headphone amplifier (0.01-Ohm output impedance) driving Sony MDR-V6 headphones (60-Ohm input impedance). The red trace was produced by inserting a 30-Ohm series resistor between the HPA2™ and the headphone input. When the resistor is inserted, the damping factor is reduced to 2. In both cases, the audio analyzer is monitoring the input to the headphones. All of the distortion shown in the red trace is developed across the 30-Ohm series resistor as a result of the mechanical motion of the headphone transducers.

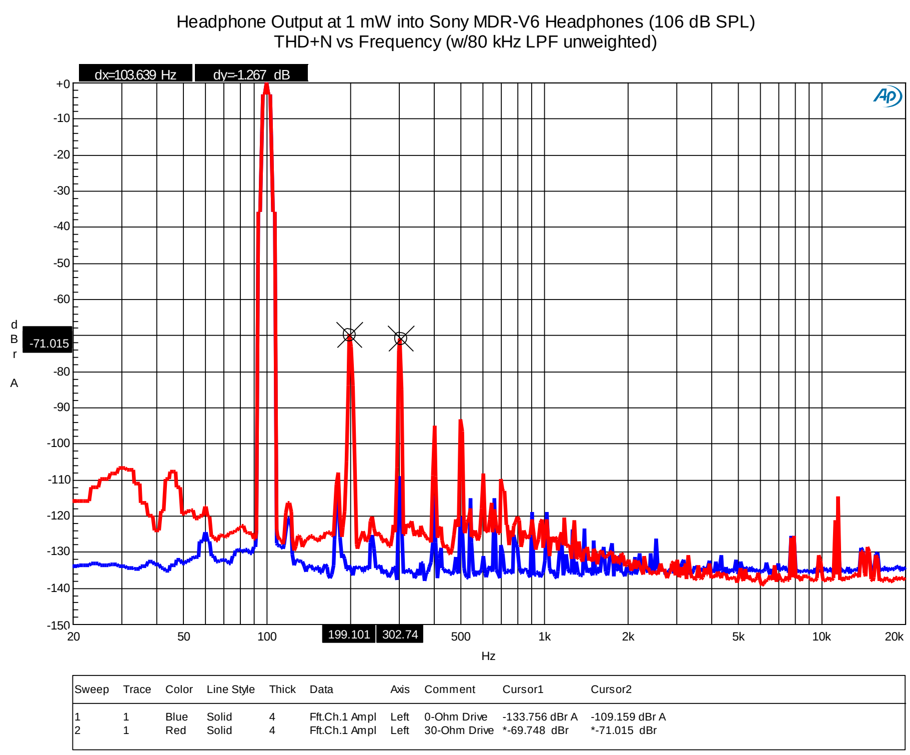
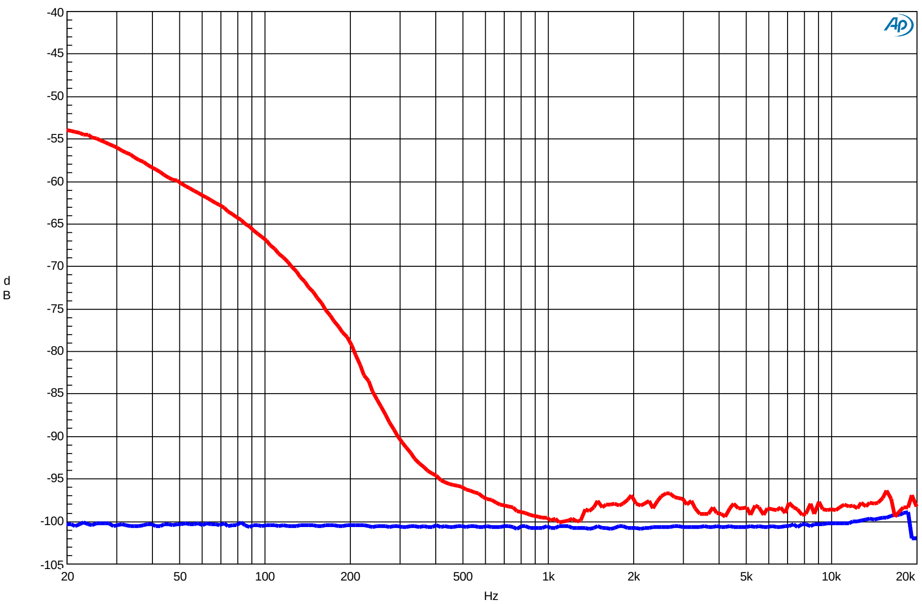


Figure 2 shows a spectrum analysis of the distortion produced at 100 Hz. The test setup is identical to the setup for Figure 1. The blue trace was produced at a damping factor of about 6,000. The red trace was produced at a damping factor of about 2. The red trace shows a 64 dB increase in 2nd harmonic distortion and a 38 dB increase in 3rd harmonic distortion.

Figures 1 and 2 clearly show that audible increases in distortion may occur when the damping factor is too low. Our own listening experiences suggested that headphones are cleaner when driven from a very low source impedance. We found the difference most noticeable when listening to solo piano recordings with the MDR-V6 headphones . At a damping factor of 2, the harmonic distortion produced by the headphones seemed to beat against the inharmonic overtones of the piano giving the impression of a poorly tuned instrument. This effect seemed to diminish when the damping factor was increased to 6000. It was this listening test that inspired Benchmark's "0-Ohm" HPA2™ headphone amplifier in 1995.

Headphone Output at 6.65 mW into Sennheiser HD 650 Headphones (106 dB SPL)
THD+N vs Frequency (w/80 kHz LPF unweighted)

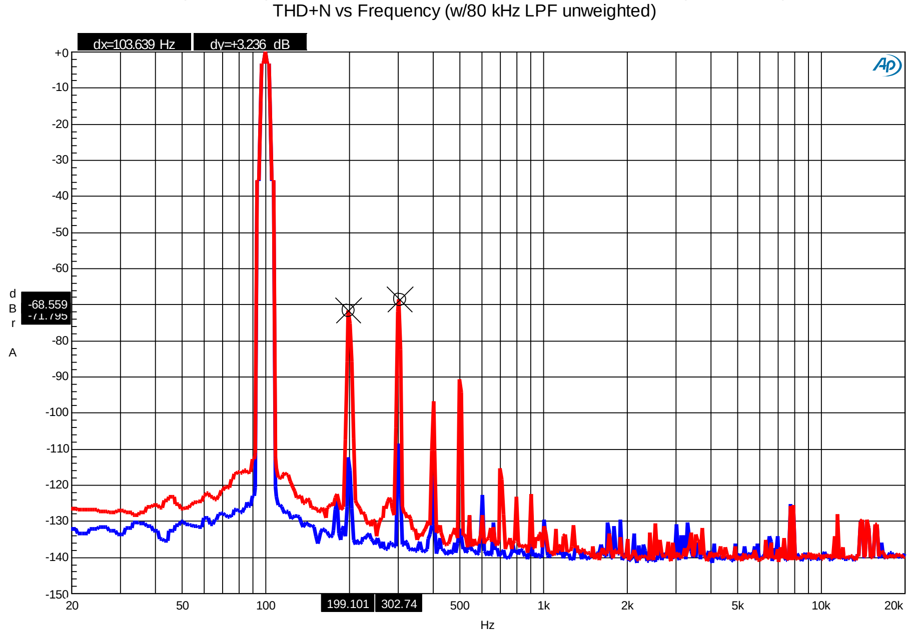


Sweep	Trace	Color	Line Style	Thick	Data	Axis	Comment
1	1	Blue	Solid	4	Anlr.THD+N Ratio	Left	0-Ohm Drive
2	1	Red	Solid	4	Anlr.THD+N Ratio	Left	30-Ohm Drive

HPA THD+N vs Frequency 300 Ohm Headphones at 0-Ohm vs 30-Ohm at 106dB.at27

Figure 3 is the same as Figure 1 except that the MDR-V6 headphones have been replaced by 300-Ohm Sennheiser HD650 headphones. The damping factor for the blue trace is 30,000. The damping factor for the red trace is 10. The red trace shows slightly better high-frequency performance than in Figure 1. This improvement is due to a 5 to 1 improvement in damping factor (10 instead of 2).

Headphone Output at 6.65 mW into Sennheiser HD 650 Headphones (106 dB SPL)
THD+N vs Frequency (w/80 kHz LPF unweighted)

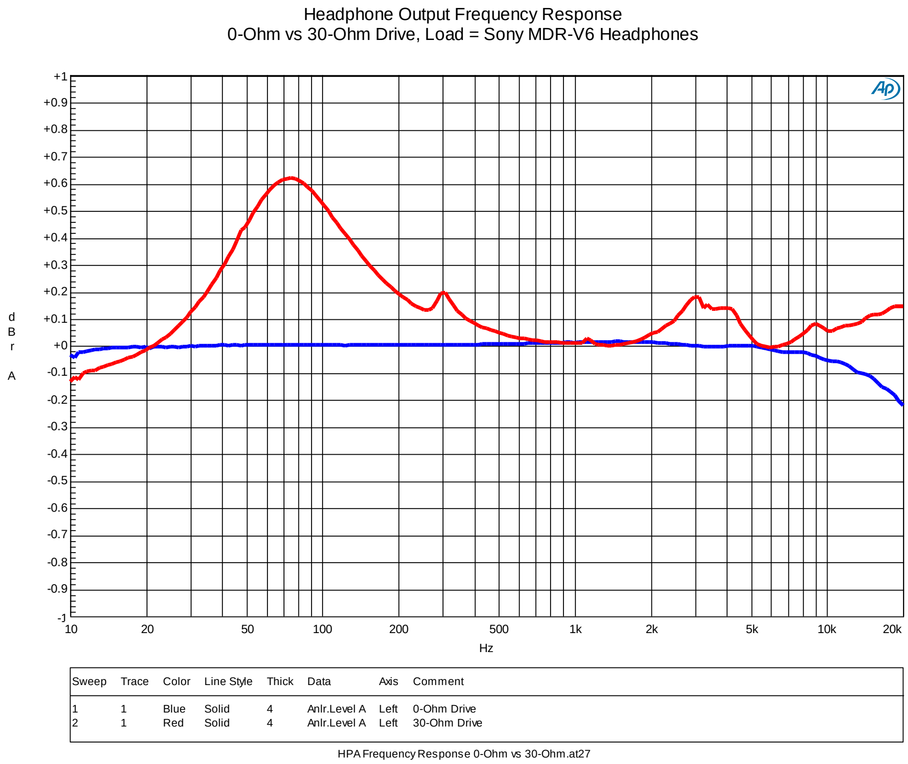


Sweep	Trace	Color	Line Style	Thick	Data	Axis	Comment	Cursor1	Cursor2
1	1	Blue	Solid	4	Fft.Ch.1 Ampl	Left	0-Ohm Drive	-112.487 dBr A	-108.661 dBr A
2	1	Red	Solid	4	Fft.Ch.1 Ampl	Left	30-Ohm Drive	*-71.795 dBr	*-68.559 dBr

HPA FFT 100Hz Tone 300 Ohm Headphones at 0-Ohm vs 30-Ohm at 106dB.at27

Figure 4 is the same as Figure 2 except that the MDR-V6 headphones have been replaced by 300-Ohm Sennheiser HD650 headphones. The damping factor for the blue trace is 30,000. The damping factor for the red trace is 10. This plot shows that the higher impedance of the HD650 headphones did little to improve performance at 100 Hz.

Figure 5 shows the frequency response variations that occur when the damping factor is too low. The damping factor for the blue trace is 6,000. The damping factor for the red trace is 2. The red trace shows a 0.7 dB variation in frequency response due to variations in the input impedance of the Sony MDR-V6 headphones. A high damping factor is essential for achieving a flat frequency response.



Note the peak in the response at 300 Hz. This corresponds to the 300 Hz resonance problem shown in Figure 1. This anomaly is not an issue when the headphones are driven from 0.01 Ohms.

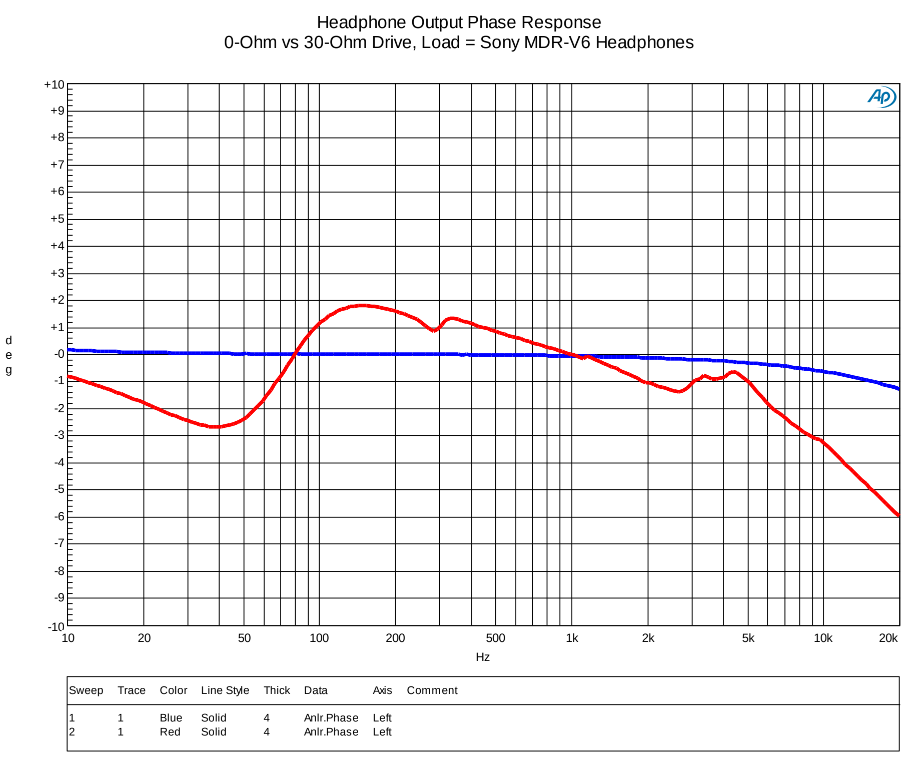


Figure 6 shows the phase response variations that occur when the damping factor is too low. The damping factor for the blue trace is 6,000. The damping factor for the red trace is 2. The red trace shows variations in phase response due to variations in the input impedance of the Sony MDR-V6 headphones. The blue trace shows that phase response is well controlled when the damping factor is 6,000. A high damping factor is essential for achieving a flat phase response.

Please note that all of the distortion, phase, and frequency problems shown in Figures 1 through 6 (red traces) are due to the mechanical transducers in the headphones working against a 30-Ohm output impedance. If we replace the 60-Ohm headphones with a 60-Ohm load resistor, <u>all</u> of the errors disappear. Headphone amplifiers are traditionally tested with a resistor load, or no load at all. Ideal resistor loads hide most of the problems that occur when traditional 30-Ohm headphone amplifiers drive headphones. For this reason, headphone specifications are often very misleading.

All measurements shown in this paper are taken at the headphone inputs. These are <u>not</u> measurements of the headphone acoustic output. Acoustic measurements may show significantly higher levels of distortion. But, the acoustic measurements can never show less distortion than the measurements taken at the headphone inputs. The 0.01-Ohm drive provided by the HPA2™ should dampen some of the distortion created by the transducers, and acoustic measurements may show this. Our listening tests suggest that this may be the case. These are areas of ongoing study in our research lab.

At a 0.01-Ohm input impedance, both sets of headphones received a clean electrical signal (as show by the blue traces). Nevertheless, in our listening tests, the HD-650 headphones always seemed to be cleaner than the MDR-V6 headphones. This implies that only some of the transducer distortion can be removed with a low-impedance headphone amplifier. Again, this is an area of ongoing study.

The frequency response and phase response variations shown is this paper should be reproducible with acoustic measurements. For example, the 0.7 dB change in the frequency response of the MDR-V6 headphones (shown in Figure 5) should be reproducible with acoustic measurements.

In summary, we have shown that a high damping factor improves audio reproduction through mechanical transducers. The formula at the beginning of this paper shows that damping factor is the ratio of the load impedance to the source impedance. Headphones typically have 60-Ohm to 300-Ohm input impedances. We used two popular headphones that are at opposite ends of this range. Both headphones showed performance improvements when the source impedance was reduced from 30-Ohms to 0.01-Ohms.

The Benchmark "0-Ohm" HPA2™ headphone amplifier used in these tests has an output impedance of 0.01 Ohms at 1 kHz. The HPA2™ achieves a damping factor of 6,000 to 30,000 at 1 kHz when driving typical (60-Ohm to 300-Ohm) headphones. The 0.01-Ohm drive impedance of the HPA2™ produced dramatic performance improvements when compared to a 30-Ohm drive impedance. Distortion at the input of the headphones was reduced by as much as 64 dB, 10 degree phase response variations were removed, and frequency response was improved by as much as 0.7 dB.

When using a 30-Ohm headphone amplifier, the damping factor can be increased slightly by selecting 300-Ohm headphones instead of 60-Ohm headphones. This change increases the damping factor from 2 to 10. Figures 3 and 4 showed that a damping factor of 10 was insufficient. Significant performance improvements were obtained by raising the damping factor to 6,000. No additional improvement was obtained by increasing from 6,000 to 30,000.

A low output impedance places significant demands on the headphone drive circuits. The HPA2™ is well suited to this task. We have shown that the HPA2™ remained nearly distortion free while driving headphones (see the blue traces in each of the figures above). In a previous white paper we examined the performance of two other "0-Ohm" headphone amplifiers and documented the differences. The HPA2™ showed significant advantages over the other two units.

Test Conditions to Produce a Damping Factor of 2:

1) Sony MDR-V6 60-Ohm Headphones
2) 30-Ohm metal-film series resistor (to degrade damping factor)
3) Benchmark HPA2™ 0.01-Ohm headphone amplifier (in DAC1 HDR) *
4) Normal listening level (106 dB peak SPL)

Test Conditions to Produce a Damping Factor of 10:

1) Sennheiser HD650 300-Ohm Headphones
2) 30-Ohm metal-film series resistor (to degrade damping factor)
3) Benchmark HPA2™ 0.01-Ohm headphone amplifier (in DAC1 HDR) *
4) Normal listening level (106 dB peak SPL)

Test Conditions to Produce a Damping Factor of 6,000:

1) Sony MDR-V6 60-Ohm Headphones
2) No series resistor
3) Benchmark HPA2™ 0.01-Ohm headphone amplifier (in DAC1 HDR) *
4) Normal listening level (106 dB peak SPL)

Test Conditions to Produce a Damping Factor of 30,000:

1) Sennheiser HD650 300-Ohm Headphones
2) No series resistor
3) Benchmark HPA2™ 0.01-Ohm headphone amplifier (in DAC1 HDR) *
4) Normal listening level (106 dB peak SPL)

Test Equipment:

Audio Precision System 2722

* The HPA2™ headphone amplifier is available in many Benchmark products, including the DAC1, DAC1 USB, DAC1 PRE, DAC1 HDR, MPA1 and PRE420. The DAC1 HDR was used for the tests published in this paper, but the results are nearly identical for all HPA2™ products.