Application Note

Design Considerations for a High-Output-Power Hi-Fi Headphone Amplifier Based on INA1650-Q1 for Automotive Applications

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ABSTRACT

This application note presents a headphone amplifier design based on the INA1650-Q1, specifically engineered for automotive audio systems. The solution meets the practical requirements of on-board headphone functionality and is suitable for scenarios including passenger-exclusive audio and noise-free in-vehicle audio experiences. To effectively drive low-sensitivity headphones and ensure sufficient volume, the amplifier must deliver ample output power over a wide range of headphone load impedances. A key design challenge stems from conflicting power output requirements: driving high-impedance headphones calls for a higher amplifier output voltage (and thus a higher supply voltage), while delivering the same power to low-impedance headphones requires a significantly higher output current. By paralleling the two channels of a single INA1650-Q1 to boost output power, this challenge is effectively resolved, enabling stable and high-performance audio amplification that complies with the stringent specifications of automotive audio systems.

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Trademarks

1 Introduction

With the continuous upgrade of automotive infotainment systems, on-board headphone functionality has evolved from a niche feature to a practical and high-demand requirement for modern vehicles. Passengers often seek personalized audio experiences—whether for enjoying music, watching movies, or participating in voice calls—without disturbing the driver or other occupants, making on-board headphone connectivity an essential component of user-centric automotive design.

However, a critical issue arises when driving low-sensitivity headphones, which require a certain level of output power to achieve satisfactory volume levels. This poses a unique technical challenge for automotive headphone amplifiers: the need to accommodate varying headphone load impedances while maintaining consistent power output. For high-impedance headphones, the amplifier must generate a higher output voltage to deliver the required power, which places greater demands on the supply voltage range. Conversely, low-impedance headphones demand a higher output current from the amplifier to achieve the same power level, testing the current-driving capability of the device. Traditional amplifier designs often struggle to balance these two requirements simultaneously, leading to compromised audio performance or limited compatibility with different headphone types.

The INA1650-Q1, a high-performance automotive-grade amplifier, is engineered to tackle these challenges head-on. This report elaborates on the design principles, circuit implementation, and performance verification of the INA1650-Q1-based headphone amplifier design, demonstrating its ability to deliver stable, high-quality audio output across diverse load conditions and meet the stringent reliability and performance standards of automotive applications.

Figure 1-1. Automotive 3.5mm Headphone Jack

2 Automotive Hi-Fi Headphone Audio System Overview

Hi-Fi, short for High-Fidelity, refers to the playback of sound with high-quality reproduction or maximum fidelity to the original audio source. Ideally, Hi-Fi audio devices can achieve ultra-low noise and distortion that are imperceptible to the human ear. As illustrated in Figure 2-1 , the block diagram of a typical Hi-Fi audio system, the Hi-Fi device converts the differential output voltage of a Digital-to-Analog Converter (DAC) into a single-ended voltage capable of driving low-impedance headphones. A differential-to-single-ended converter is employed to convert differential signals into single-ended signals for headphone driving.

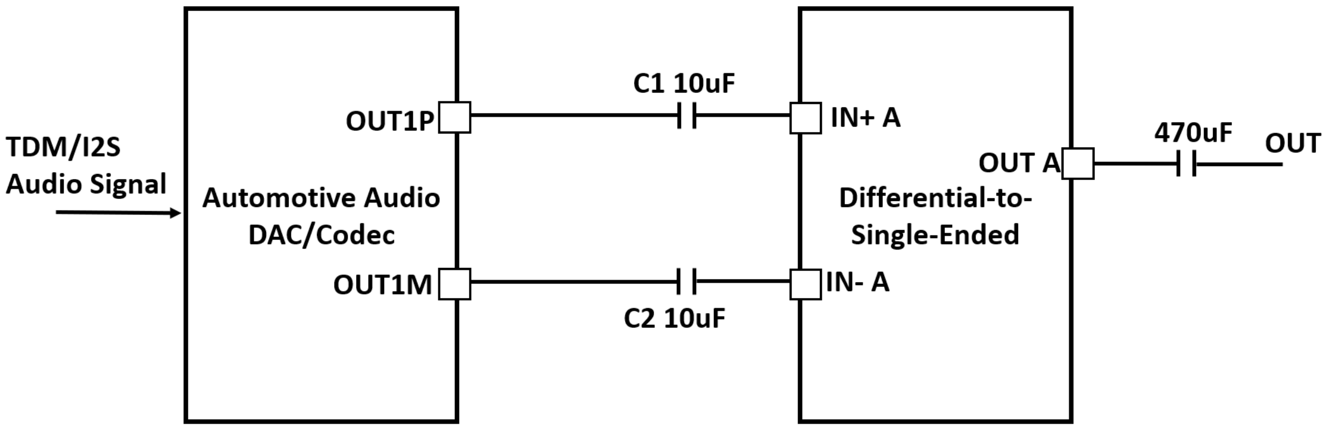

Figure 2-1. Block Diagram of Automotive Hi-Fi Audio System

Most of consumer-grade headphones are single-ended designs (3.5mm/6.35mm interface, requiring only one signal path + ground wire). For single-ended mode, there are AC-coupled and DC-coupled modes. But the single ended DC-coupled mode will contain a DC common mode voltage. This results in high power consumption, and hence DC-coupled single ended mode is not recommended. The single ended AC-coupled mode is better designed for headphone applications. When operating in single-ended AC-coupled mode, the AC-coupling capacitor requires careful selection. This capacitor forms a high-pass filter with the load, and its value has a significant impact on the audio frequency response. A smaller value capacitor will attenuate lower audio frequencies, resulting in a loss of bass response. For this reason a large AC-coupling capacitor is required to block the DC bias from the DAC output while preserving the desired audio frequency range.

$$F_C = \frac{1}{2 \times 3.14 \times C \times Z_{load}} \quad (1)$$

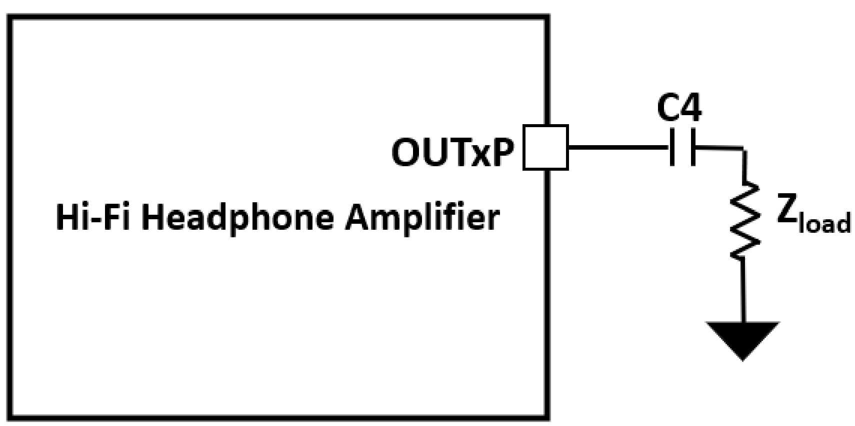

Figure 2-2. DC-Coupled Differential Mic Input Hardware Design

For headphone/headset (32Ω) applications: Use ≥470µF to maintain fc = 10Hz.

2.1 Key Technical Specifications of Automotive Hi-Fi Audio Systems

The core technical specifications of an automotive Hi-Fi audio system include Signal-to-Noise Ratio (SNR) and Total Harmonic Distortion plus Noise (THD+N).

Signal-to-Noise Ratio (SNR) is defined as the ratio of the output signal power to the output noise power of an audio device at the same reference point, typically expressed in decibels (dB), as shown in Equation (2). In the formula, P_{signal} represents the output signal power and P_{noise} denotes the output noise power. A higher SNR value indicates a lower level of noise superimposed on the audio signal, which corresponds to a higher sound reproduction quality, and vice versa. For automotive Hi-Fi audio systems, the SNR specification is typically required to be above 105db.

$$NR(dB) = 10log\left(\frac{P_{signal}}{P_{noise}}\right) \tag{2}$$

Total Harmonic Distortion plus Noise (THD+N) is a critical performance parameter for characterizing audio reproduction quality, and its predicted value can be calculated per Equation 3, where V_n represents the RMS value of the total output noise voltage and V_f denotes the RMS value of the fundamental frequency output voltage. The THD+N performance of an audio system is determined by multiple design factors, including a high-quality audio signal source, DACs and operational amplifiers with ultra-low noise and distortion, ultra-low noise power supplies, and optimized PCB layout and routing. For automotive Hi-Fi audio systems, the typical specification requires THD+N < 0.001%. Equation 3 mathematically shows that THD + N is defined as the ratio of the harmonic power measurements summed together to the power of the fundamental frequency.

$$THD + N(\%) = 100\% \times \sqrt{\frac{\sum_{i=2}^{\infty}\left(V_i^2 + V_n^2\right)}{V_f^2}} \tag{3}$$

Where:

V_i RMS voltage of the i-th harmonic of the fundamental (i=2,3,4…)

V_n RMS noise voltage of the circuit

V_f RMS voltage of the fundamental

In addition, automotive applications impose stringent and detailed requirements for Electromagnetic Interference (EMI) performance of chips. The core requirement is compliance with international and industry standards, as well as adaptation to the complex electromagnetic environment of vehicles. Automotive chips are typically required to operate at an ambient temperature of 85°C. Therefore, the EMI performance and thermal characteristics of devices adopted in the Hi-Fi system must be considered in the design. Automobiles are generally powered by a 12V battery, so TI recommends that the supply voltage of the Hi-Fi system be less than 12V with a unipolar power supply configuration.

2.2 Design Requirements for Automotive Hi-Fi Headphone Audio Systems

For automotive applications, the design requirements of the Hi-Fi headphone audio system are specified as follows:

Table 2-1. Design Targets

Supply Voltage	<12v
THD+N (1kHz/32 Ω)	<0.001%
Maximum Output Power	100mW

To verify sufficient volume for low-sensitivity headphones, a headphone amplifier is required to deliver significant output power across a full range of load conditions. This poses a design challenge: delivering a specific power to a high-impedance headphone load demands a higher amplifier output voltage (and thus a higher supply voltage), while delivering the same power to a low-impedance headphone requires a considerably higher amplifier output current.

Output Power Limitations

The output power of an operational amplifier (op amp) is constrained by multiple factors. For high-impedance loads, the slew rate and full-power bandwidth of the op amp are the primary limiting factors. The full power bandwidth is the frequency range over which the op amp can deliver maximum output power without significant distortion. For low-impedance loads, the output current limit of the op amp becomes the dominant constraint. Additionally, the current limit is subject to thermal effects: high power dissipation inside the op amp causes a rise in its junction temperature, which in turn reduces the current limit and consequently increases audio distortion.

This issue is particularly pronounced when driving low-impedance loads with a relatively high supply voltage, as the high output current required by low-impedance loads leads to rapid excessive power dissipation, which significantly restricts the available output power.

Output Power Enhancement

The power delivered to low-impedance headphones can be increased by using a lower supply voltage, which reduces the power dissipation of the op amp. However, this may not be a viable design in some applications, as a reduced supply voltage will significantly degrade the power delivery to high-impedance headphones. Selecting an op amp with automotive higher power rating can mitigate the impact of power dissipation, yet many applications benefit substantially from the superior performance of low-power op amps such as the INA1650-Q1. In such cases, paralleling two channels of the op amp can deliver the required output power.

The power requirement of most general consumer-grade headphones ranges from 10 mW to 100 mW, a range that meets the daily listening needs of most users. This design is optimized for a maximum power requirement of 100 mW, a value sufficient to drive a wide range of headphone models. A headphone impedance RHP of 32 Ω is selected for the design, as this is a standard impedance value for portable audio headphones. Therefore, the required output voltage for a 32 Ω headphone can be calculated as follows:

$$V_O = \sqrt{P_{IN} \times R_{HP}} = \sqrt{100mW \times 32} = 1.789V_{RMS} \quad (4)$$

3 Automotive Hi-Fi Headphone Audio System Working Principle and Circuit Design

Given the stringent performance requirements for automotive high-fidelity headphone amplifier design, a DAC with differential output capability is selected. The INA1650-Q1, a dedicated audio amplifier, converts the differential voltage output from the DAC into a single-ended voltage, and the resulting single-ended signal drives the headphone load to produce audio output.

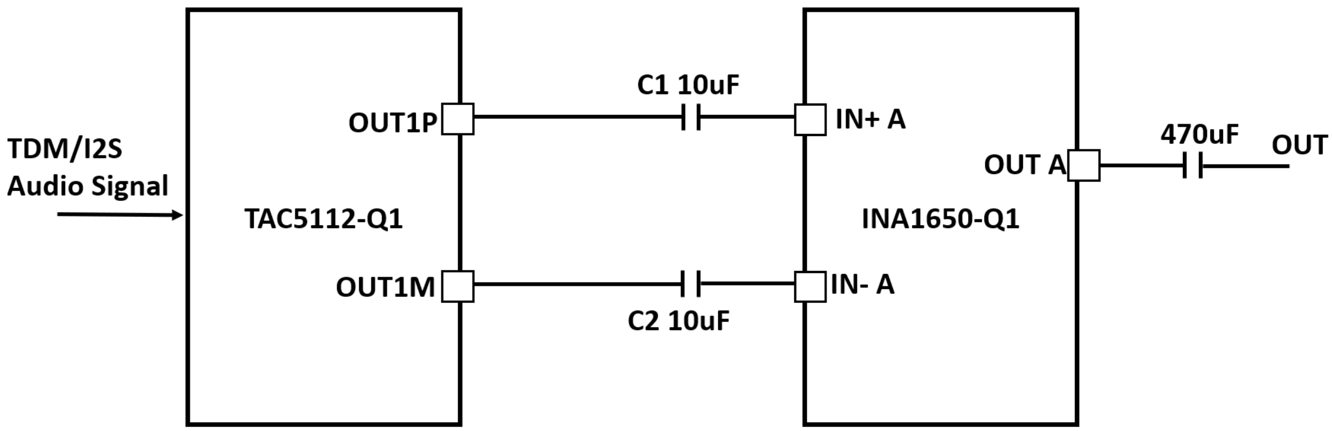

Figure 3-1. Simplified Schematic of Automotive Hi-Fi Headphone Amplifier

3.1 DAC Circuit Design

TI offers the TAx5x1x-Q1 series for automotive applications, an automotive-grade family of high-performance audio ADC/DAC/CODEC devices that includes three major subfamilies: TAC, TAA and TAD, covering both mono and stereo audio configurations. These devices integrate a rich set of features, including multiple analog input/output channels, high signal-to-noise ratio (SNR), low total harmonic distortion plus noise (THD+N), and support for a variety of audio formats, making them designed for in-vehicle infotainment, ANC/RNC, eCall and other automotive audio applications.

Within this series, the TAC5212-Q1 is an automotive high-performance audio DAC, featuring 2 Vrms differential output with 114dB dynamic range for stereo channels, or 1Vrms single-ended output with 107dB dynamic range for quad channels. The device supports both differential and single-ended input and output configurations, enabling flexible integration into automotive audio systems.

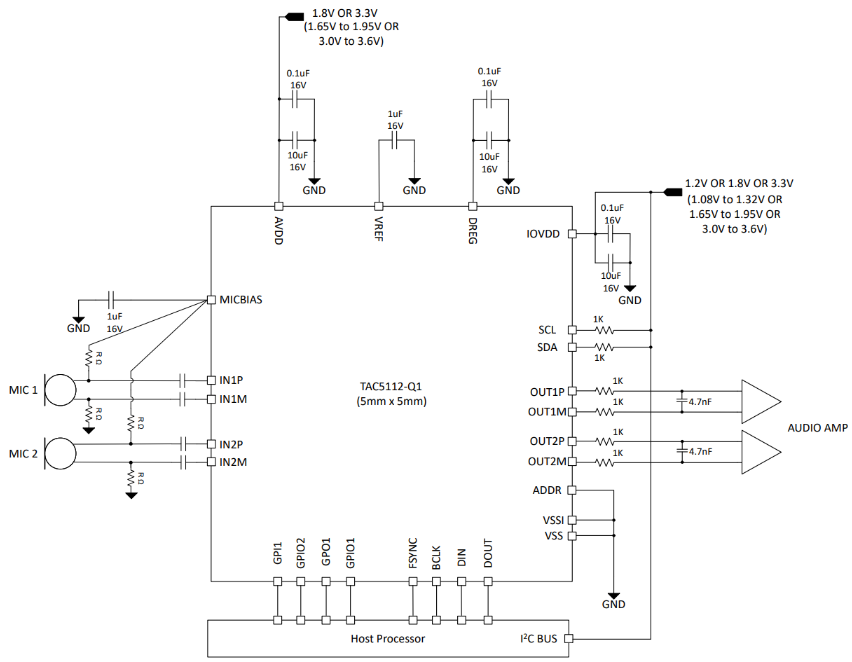

Figure 3-2. Audio Codec TAC5112-Q1 Application Circuit Schematic

3.2 Differential-to-Single-Ended Circuit Design

The vast majority of consumer-grade headphones adopt a single-ended design (3.5mm/6.35mm interface, requiring only one signal channel plus a ground line), while professional audio links (for example, DAC output, preamplification) typically use differential signals to verify signal transmission quality. To leverage the advantages of differential signals for high-fidelity headphone audio design, the differential-to-single-ended circuit is developed for this specific application.

The differential-to-single-ended circuit not only takes advantage of the transmission performance of differential signals but also matches the single-ended input requirements of headphones through signal conversion, combining the strengths of differential signals to meet the application needs of single-ended loads. The circuit optimizes signal quality by virtue of the anti-interference and low-distortion characteristics of differential signals, then adapts to the single-ended operating mode of headphones via signal conversion, ultimately fulfilling the high-fidelity pursuit of Hi-Fi headphone amplifiers. This design is particularly common in high-end headphone amplifiers and is one of the key technologies for audio quality improvement.

Audio amplifiers are commonly used to implement audio differential-to-single-ended circuits. TI has developed a series of high-performance audio amplifiers designed for the most discerning audiophiles, among which several automotive-grade models with outstanding performance are listed as follows: OPA1642-Q1, OPA1612-Q1, OPA1662-Q1 and INA1650-Q1.

Table 3-1. Key Performance Parameters of Automotive-Grade Audio Amplifiers

Amplifier PN	THD+N(G = +1, f = 1kHz, VO = 3VRMS) (dB)	Maximum output current	Support a single-polarity power supply?
OPA1642-Q1	-126	+ 36/-30mA/CH	YES
OPA1612-Q1	-136	+ 55/-62mA/CH	YES
OPA1662-Q1	-124	+ 50mA/CH	YES
INA1650-Q1	-108.1	±75mA/CH	YES

The most importment consideration for op amp selection in differential-to-single-ended circuits is to maintain low distortion and noise while meeting the output power requirements. As specified previously, the designed output power is 100mW, a value sufficient to drive a wide range of headphone models, corresponding to 1.789Vrms (2.529V peak). For a typical 32Ω headphone, the required maximum output current is 79mA. The two channels of INA1650-Q1 are fully symmetrical and can be paralleled to boost output power. INA1650-Q1 is selected for the design based on a comprehensive consideration of output power and THD+N performance.

Practically, the INA1620 is the optimal design in terms of performance, featuring a THD+N of -132dB, a maximum output current of 145mA, and a large-size thermal pad. This is the first choice if the device had obtained automotive-grade certification. However, among the currently available automotive-grade designs, INA1650-Q1 stands out as the best option due to THD+N performance, high output current, and unipolar power supply compatibility.

INA1650-Q1 offers three additional key advantages:

1. This device integrates on-chip input buffers, which prevent external resistances (for example, from PCBs, connectors or cables) from disrupting the precise matching of the internal 10kΩ resistors— a mismatch that would degrade the high common-mode rejection ratio (CMRR) of the difference amplifier.
2. This device integrates four pairs of high-precision matched thin-film resistors, which can be directly used as the external resistors of the differential amplifier without the need for additional off-chip resistors. Thin-film resistors are typically expensive and occupy considerable PCB space, and these issues are effectively addressed by the on-chip integrated resistors of INA1650-Q1.
3. This device incorporates an on-chip EMI filter, which significantly mitigates EMI issues— a critical feature for automotive applications with stringent EMI requirements.

INA1650-Q1 supports unipolar power supply, which is preferred for automotive applications since bipolar power supply typically involves higher implementation costs. TI recommends powering the INA1650-Q1 with a low-dropout regulator (LDO), which can provide a power supply with ultra-low noise and high power supply rejection ratio (PSRR) as required by the Hi-Fi audio system.

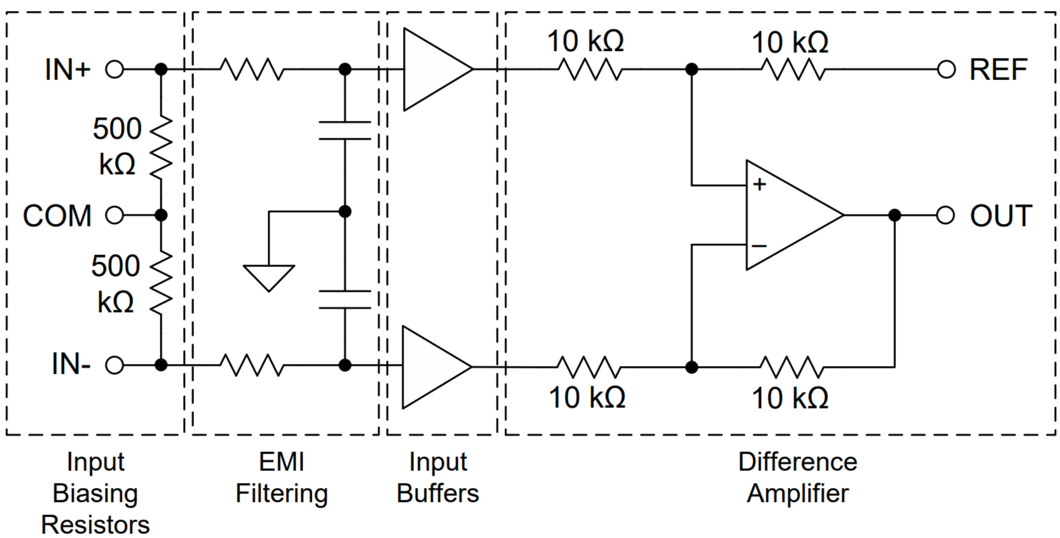

Figure 3-3. INA1650-Q1 Audio Signal Path (Single Channel Shown)

4 Simulation

Figure 4-1 shows the simulation schematic of the automotive Hi-Fi audio system. The audio DAC is enclosed in the red box on the left, the differential-to-single-ended circuit based on dual-channel parallel operation of the INA1650-Q1 is in the middle red box, and the equivalent model of the headphone impedance is in the red box on the right. The two parallel channels combine their Channel A and Channel B outputs via a 1 Ω balancing resistor, which ensures equal sharing of the load current between the two output channels. TINA-TI™ is adopted as the simulation software for the design.

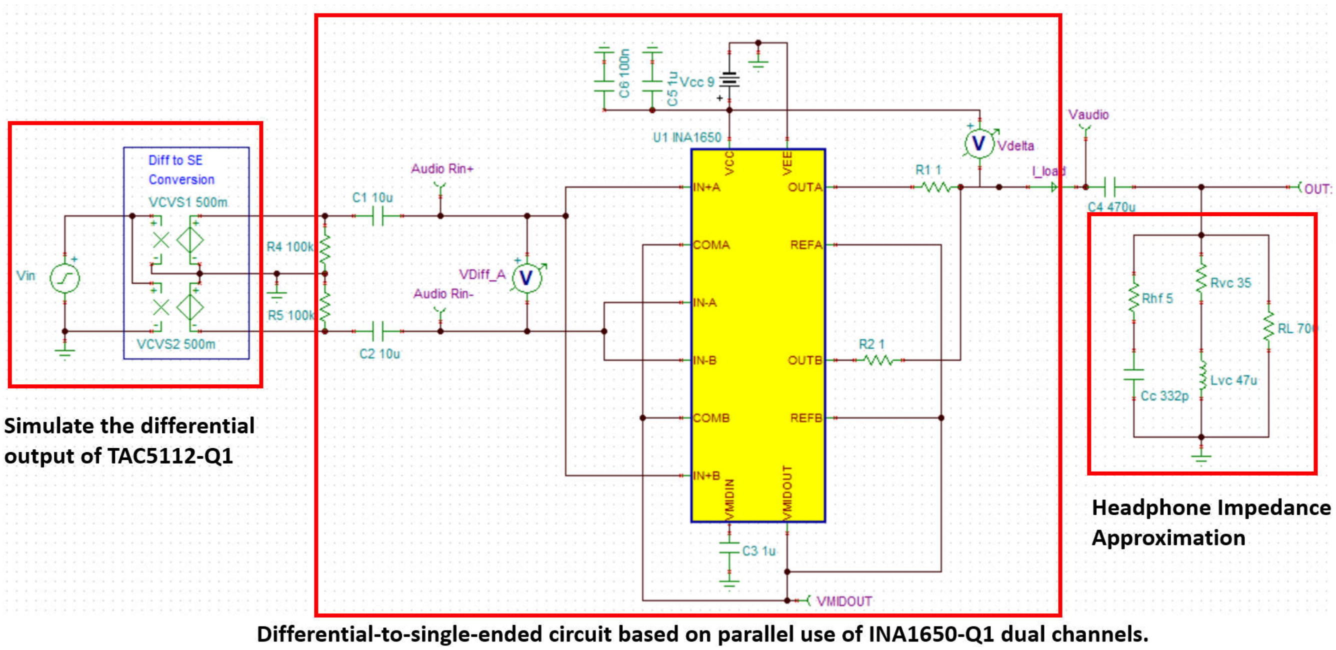

Figure 4-1. Automotive Hi-Fi Audio System Simulation Schematic

4.1 Transient Response Simulation

The audio Codec TAC5112-Q1 is modeled in TINA-TI™ as the input of the audio amplifier, with an input waveform of a 10kHz sine wave at 1.789V_{rms} (2.53V peak). The simulation results show that the differential amplifier can output the desired voltage at the output terminal, with V_{out}= 2.53V = 1.789VRMS.

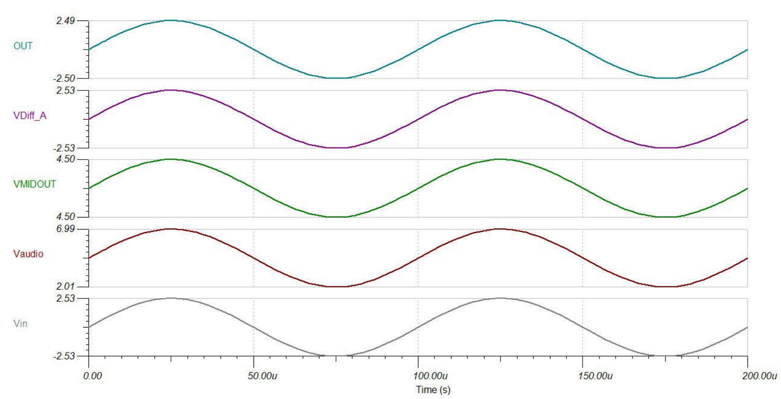

Figure 4-2. Transient Response Curve

4.2 Noise Analysis

The noise analysis function of TINA-TI™ was used with the bandwidth set to 1Hz–100kHz. Simulation results show that at 20kHz, the signal-to-noise ratio (SNR) reaches 109.52dB with a total output noise voltage of 3.34uVRMS.

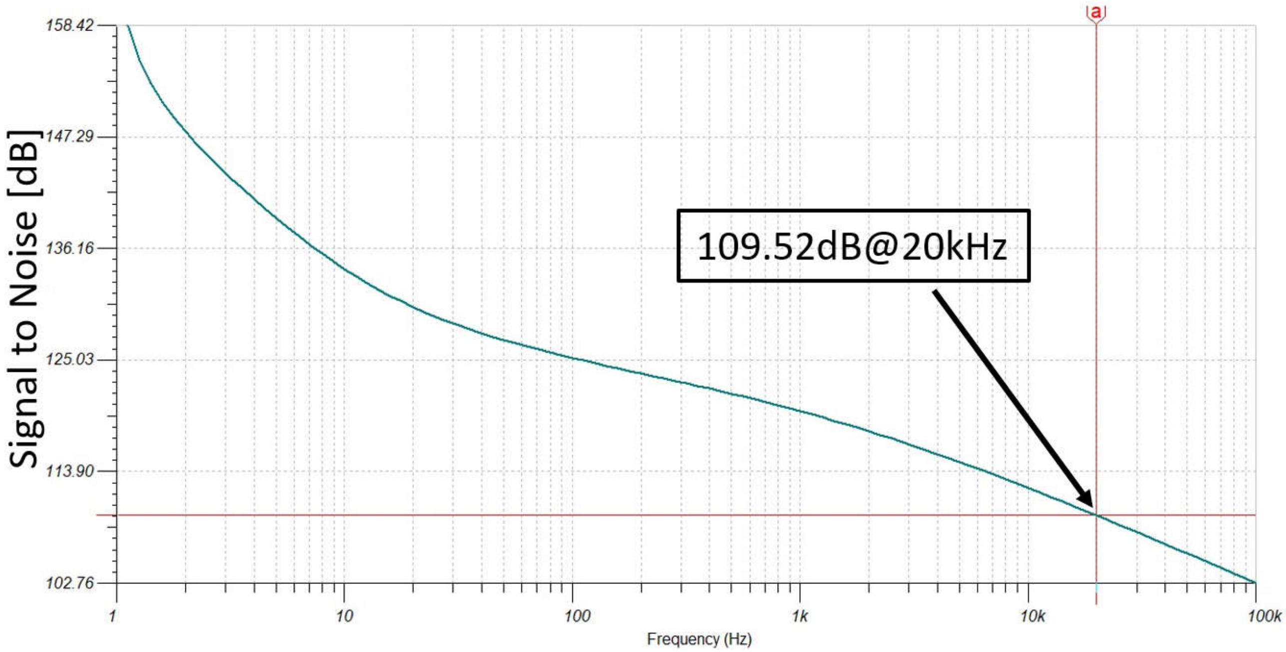

Figure 4-3. Signal-to-Noise Ratio Simulation Result Curve

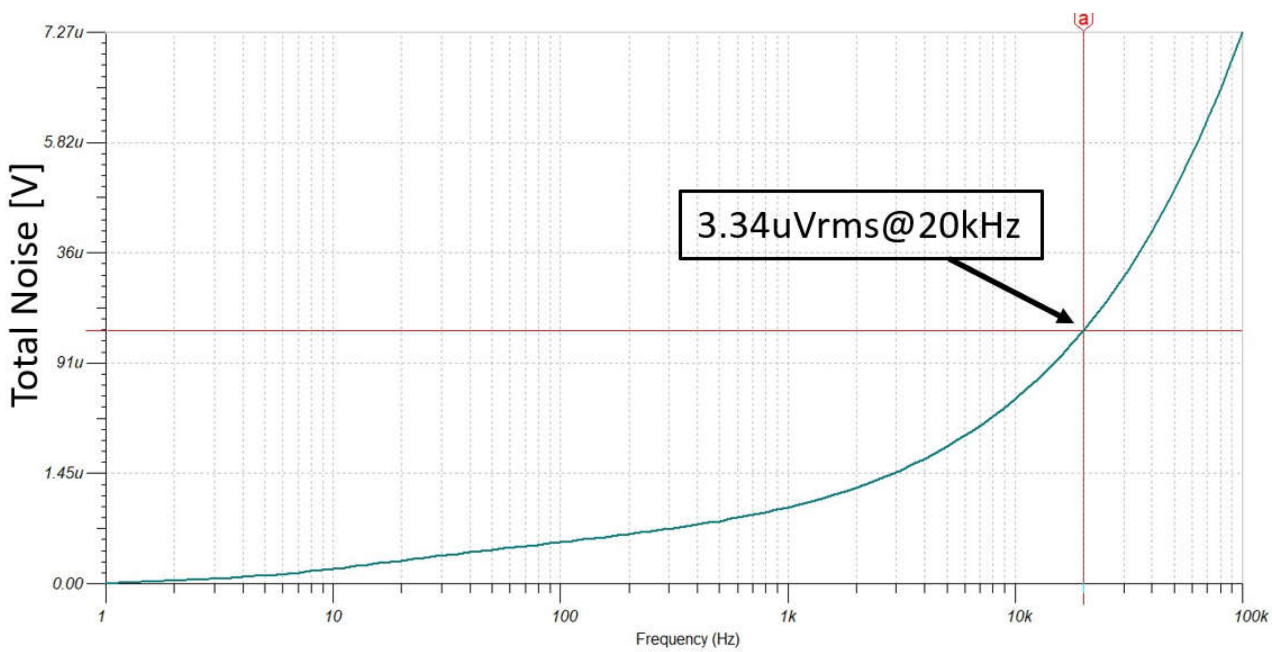

Figure 4-4. Total Output Noise Simulation Result Curve

4.3 Power Consumption Simulation and Thermal Calculation

To simplify power calculations, power calculation can be simplified by simulating power instead of performing complex calculations. The method is as follows:

Using the measured values V_{delta} (The voltage applied to the INA1650-Q1) and $I_{\_Load}$, multiply them using Tina's post-processing formula to obtain the power. By clicking on the power curve and going to Process > Averages, the RMS power can be calculated, which is 258.02mWrms..

To estimate the temperature rise, based on the INA1650-Q1 thermal parameter of θJA of 97°C/W, the resulting temperature rise is: 258.02mW × 97°C/W = 25.03°C. Adding this temperature rise to the 85 °C ambient temperature, we get a die temperature of 110.03°C. However, consider the power consumption of the device itself. With an Iq of 10mA and a supply voltage of 9V, the device consumes an additional 90mW (10mA × 9V) of power. This adds 8.73°C (90mW * 97 °C/W) to the die temperature, resulting in a total die temperature of 118.76 °C.

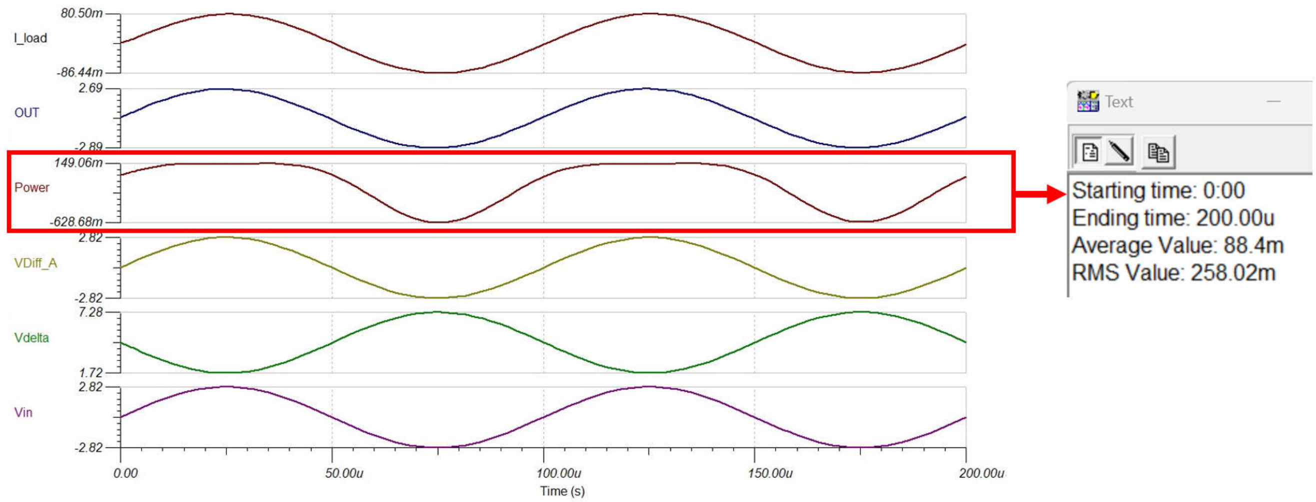

Figure 4-5. Power Simulation Results

Based on the INA1650-Q1 data sheet, at a die temperature of 125 °C, the maximum current the device can provide is approximately 53mA. By using parallel amps, a perfect doubling of current will not be acheived, but the user still obtains more current than a single amp alone. For the design's required maximum output power of 100mW, a peak drive current of 80mA is needed, which is achievable with the INA1650-Q1 via its dual-channel parallel configuration.

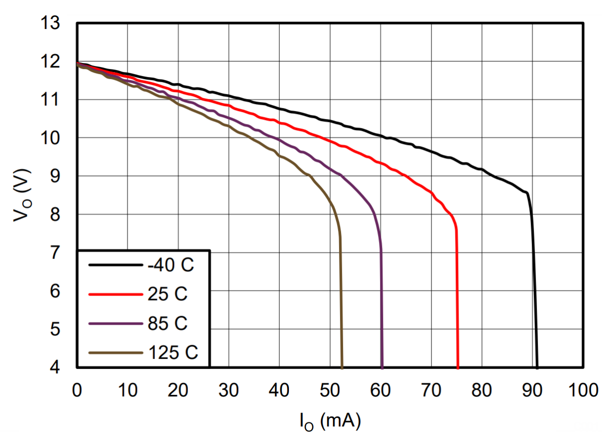

Figure 4-6. INA1650-Q1 Positive Output Voltage vs Output Current

5 Experimental Test

The experimental circuit can be constructed by utilizing the TAC5112-Q1 EVM and INA1650-Q1 EVM. The DAC output mode of the TAC5112-Q1 is configured to differential output, and the dual-channel inputs of the INA1650-Q1 are connected in parallel. The differential output of the TAC5112-Q1 is then connected to the parallel inputs of the INA1650-Q1. Set the DC power supply to 9V. A 32Ω metal film resistor is adopted to simulate the headphone load for the test, and the actual test scenario is shown in Figure 5-1.

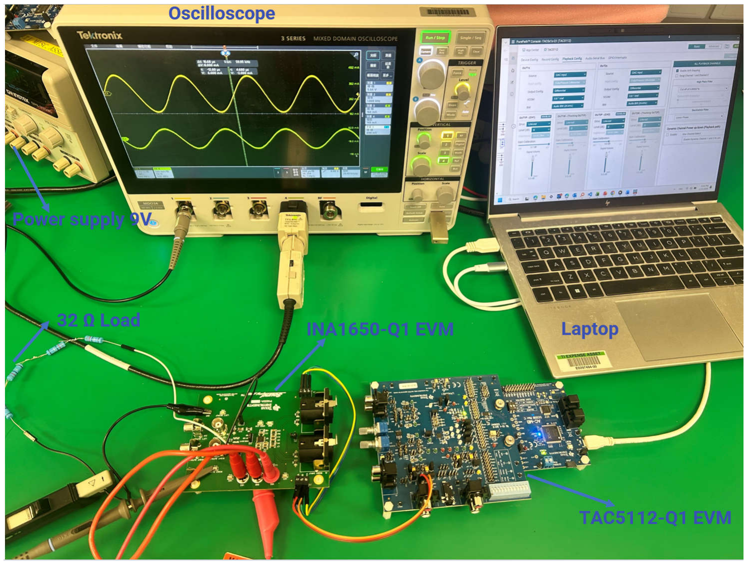

Figure 5-1. Experimental Test Prototype

Figure 5-2 shows the differential output waveform of the TAC5112-Q1, the output waveform after the INA1650-Q1 performs differential-to-single-ended conversion, and the load current waveform when driving a 32Ω load at a power of 100mW. Among them, the peak-to-peak value of Vout is 5.20V (1.84VRMS), and the peak-to-peak value of Iout is 172mA. Observe that the output waveform of the designed High-Output-Power Hi-Fi Headphone Amplifier exhibits no distortion or attenuation.

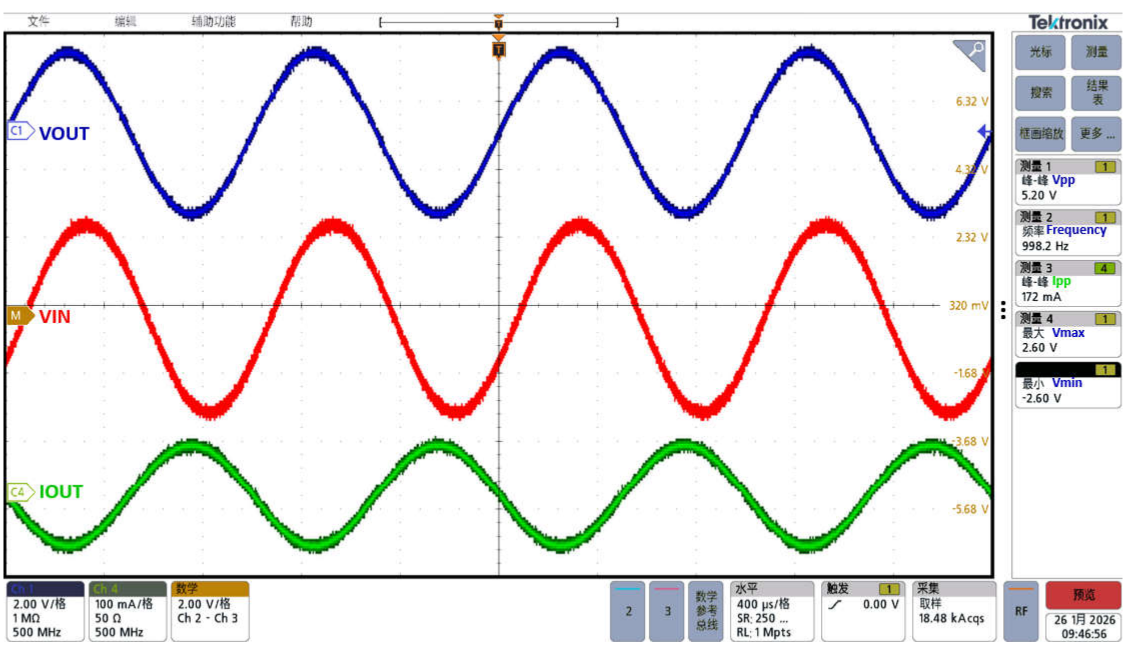

Figure 5-2. Dynamic Waveform Testing

To characterize the audio performance of the designed High-Output-Power Hi-Fi Headphone Amplifier, a 1kHz sinusoidal differential signal with an amplitude of 1.789Vrms was directly fed to the INA1650-Q1 via an audio analyzer (AP). The test was conducted with a 32Ω resistive load, and the experimental circuit was constructed as illustrated in Figure 5-3.

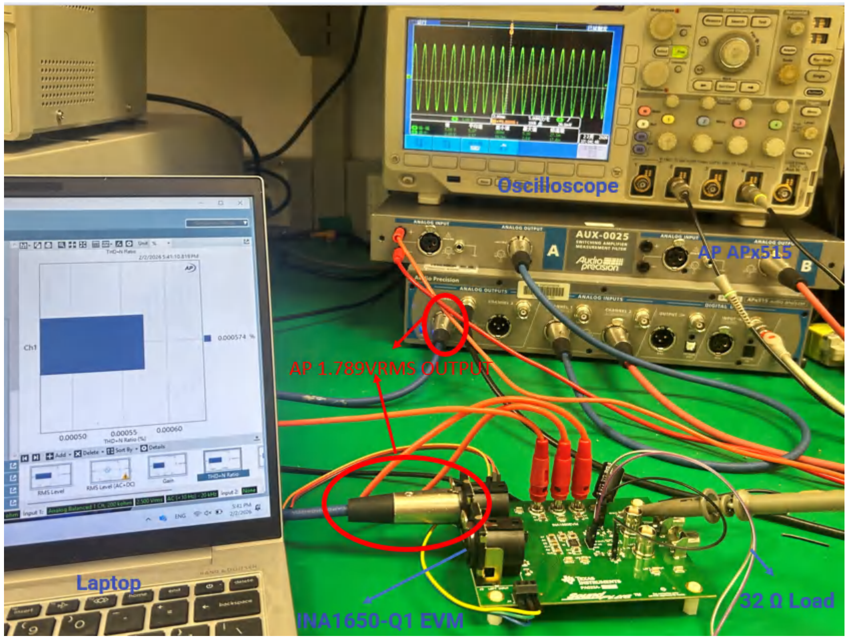

Figure 5-3. INA1650-Q1 THD+N Experimental Test Bench

At an output power of 100 mW (corresponding to 1.789 VRMS across 32 Ω), the measured total harmonic distortion plus noise (THD+N) of the INA1650-Q1-based High-Output-Power Hi-Fi Headphone Amplifier is 0.000613%, as shown in Figure 5-4. The experimental results are in good agreement with the simulation results, which fully meets the THD+N specification of < 0.001% for automotive Hi-Fi audio systems.

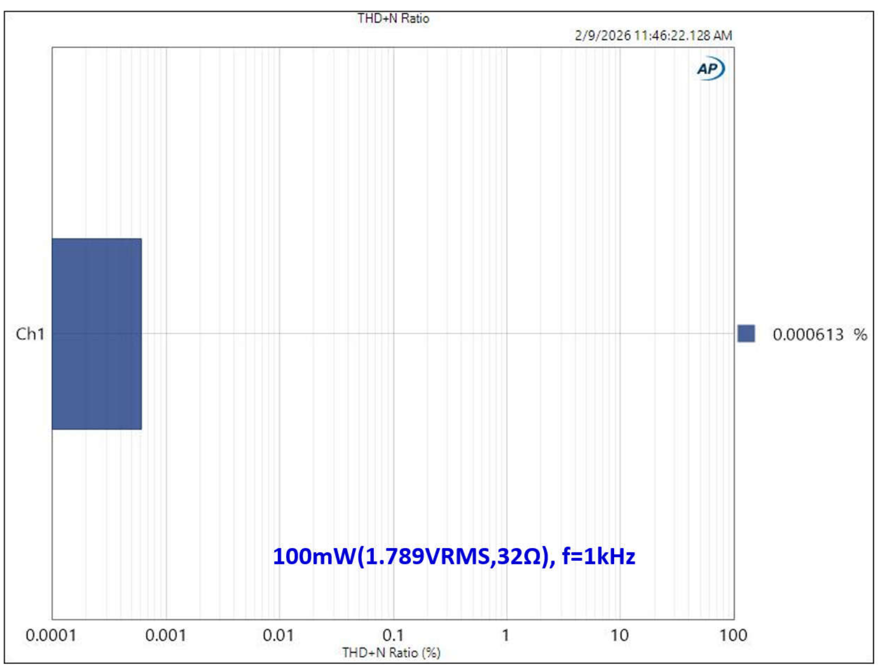

Figure 5-4. INA1650-Q1 100mW output THD+N test result

Figure 5-5 shows the THD+N test data at different output VRMS values. When the output amplitude exceeds 0.7 VRMS, the THD+N results are all below 0.001%. At an output amplitude of 100 mVRMS or 500 mVRMS, the FFT shows a fundamental frequency of 1 kHz, while the harmonics lie within the noise floor of the op-amp and are not visibly apparent, as detailed in Figure 5-6. This represents the noise-dominated region of the curve. As the output amplitude increases, the harmonics increase and rise above the noise floor of the op-amp. The FFT plots for output amplitudes of 1 VRMS and 1.789 VRMS clearly show these harmonics, as illustrated in Figure 5-7.

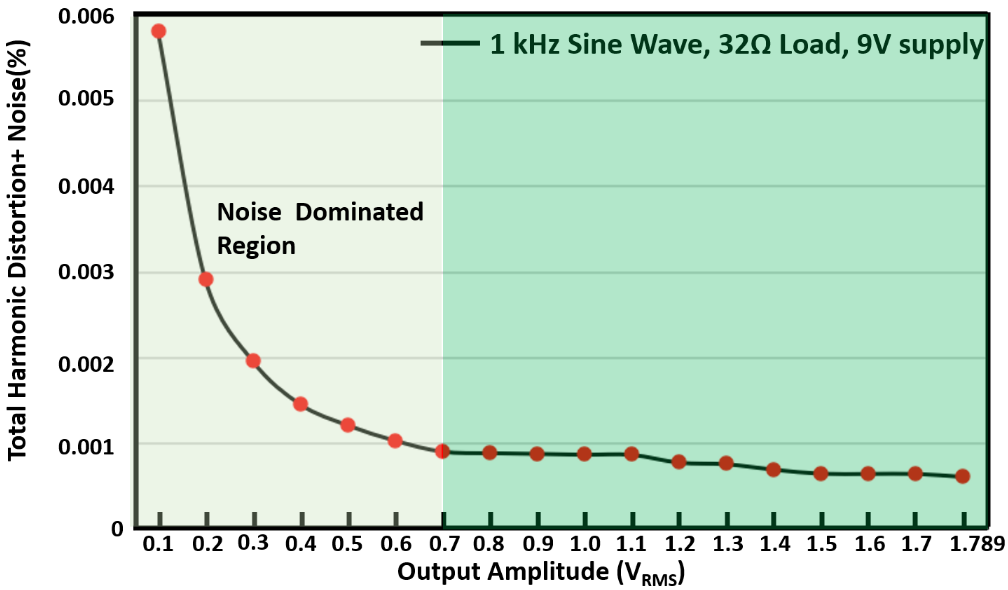

Figure 5-5. THD+N Test Data at Different Output VRMS Values

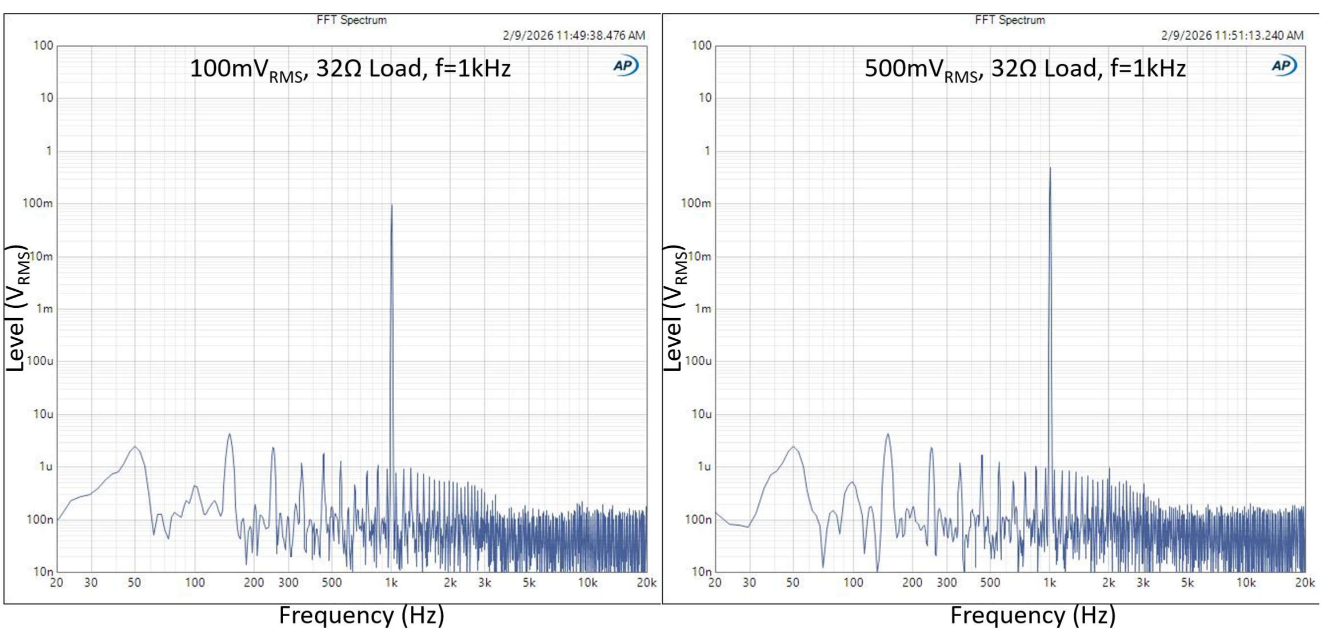

Figure 5-6. Noise-Dominated Region FFT Test Waveform

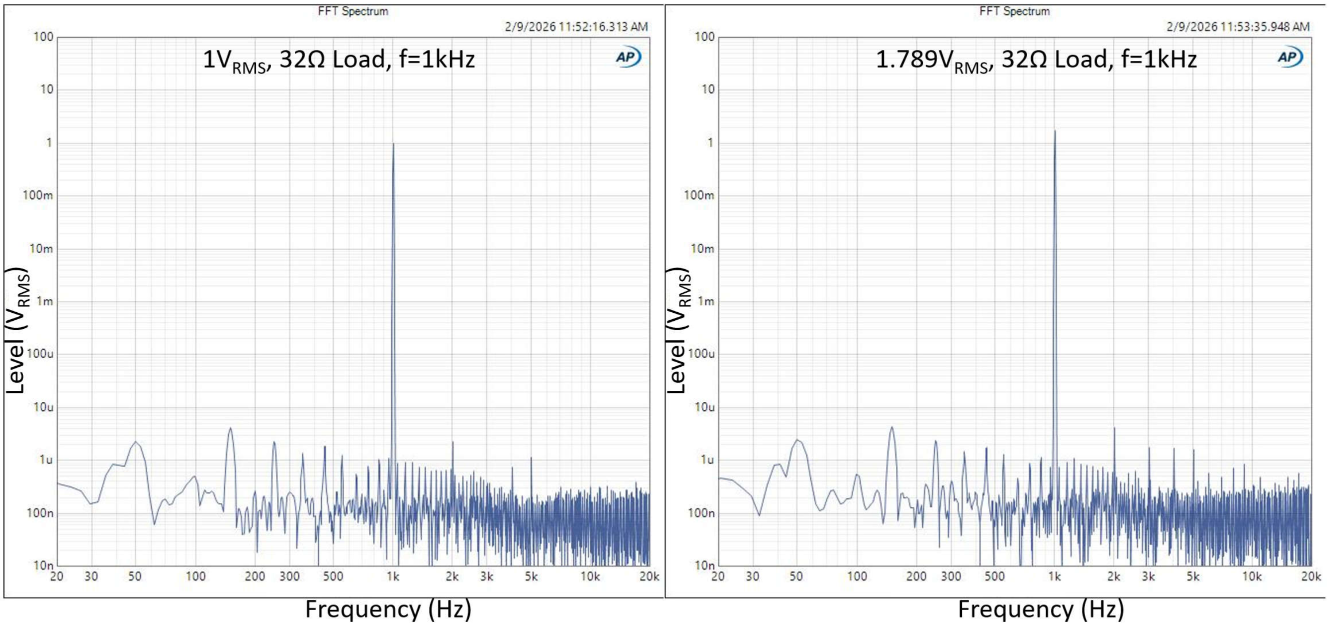

Figure 5-7. VRMS Output and 1.789V VRMS Output FFT Test Results

To achieve a larger output voltage amplitude while avoiding the distortion-dominated region for the INA1650-Q1, sufficient supply voltage must be provided first. Insufficient supply voltage causes output clipping, which leads to a rapid increase in harmonics. The output characteristics shown in Figure 5-8 can be used to verify the INA1650-Q1 operates within its linear region. A 9V single-supply configuration is used in this application note.

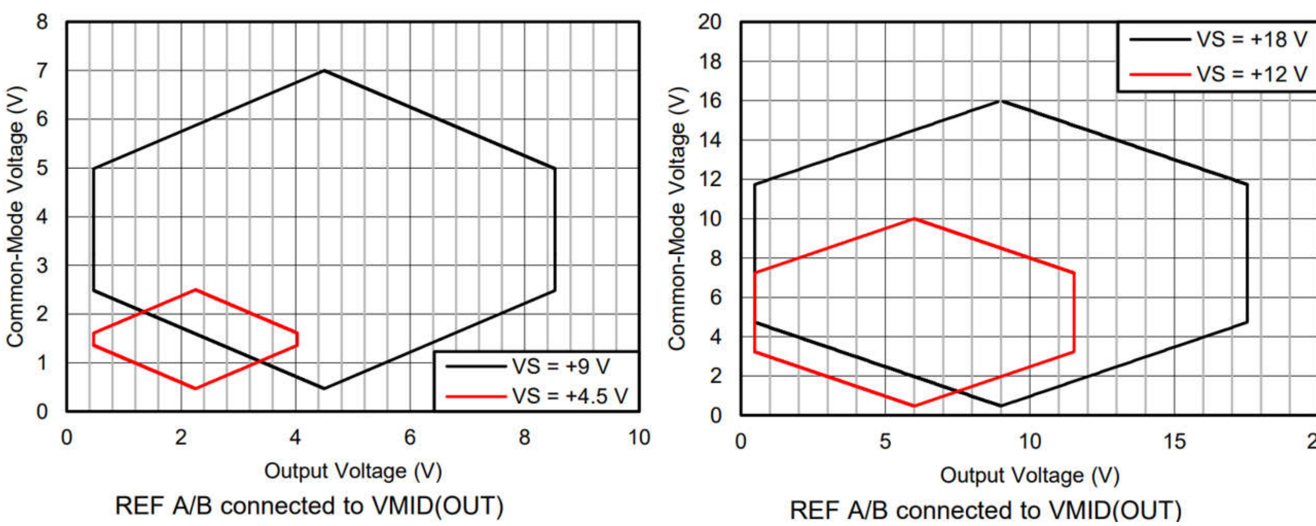

Figure 5-8. INA1650-Q1 Input Common-Mode Voltage vs Output Voltage Feature

Thermal Performance Testing presents the thermal performance of the INA1650-Q1 when driving a 100 mW load, with a temperature rise of only 14.4°C (36.1°C - 21.7°C). Experimental tests lead to the conclusion that the INA1650-Q1 can still drive a 100mW load normally even at an ambient temperature of 85°C, without exerting a significant impact on audio performance.

Figure 5-9. Thermal Performance Testing

6 Summary

This application note presents an automotive high-output-power Hi-Fi headphone amplifier design using the INA1650-Q1. This meets strict automotive requirements: < 12V single supply, THD+N < 0.001%, and 100 mW output power. A dual-channel parallel structure boosts output current to drive 32Ω headphones. With integrated buffers, precision resistors, and EMI filters, the design achieves excellent audio performance. Measurements show a THD+N of 0.000613% (32Ω,100mW), verifying low distortion and high output capability. Both simulation and test results confirm robust high-power operation, offering a practical reference for automotive infotainment audio designs.

7 References

1. Texas InstrumentsTAC5112-Q1 Automotive low-power stereo audio codec with 105 dB dynamic range ADC and 114 dB dynamic range DAC datasheet (Rev. A) datasheet.
2. Texas Instruments, INA165x-Q1 SoundPlus™ High Common-Mode Rejection Line Receivers datasheet (Rev. C) datasheet.
3. Texas Instruments, A High-Power High-Fidelity Headphone Amplifier for Current Output Audio DACs Reference Design (Rev. C), reference design.
4. Texas Instruments, How to Measure Total Harmonic Distortion of an Op-Amp and THD + N Fundamentals application note.

8 Revision History

Changes from Revision * (March 2026) to Revision A (May 2026)	Page
• Corrected typo	4

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