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A Low Distortion Audio Amplifier

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Abstract: The paper presents a design and assembly of a high-quality audio amplifier. The design is simple, and it can achieve extremely low Total Harmonic Distortion (THD) less than −100 dB for a bookshelf speaker with output power levels up to 10 W. The solution for a high-quality output are transistor pairs used in the input stage along with a simple topology that does not need matched transistor pairs for a power stage. Such input and output stages were closely analyzed at different bias currents. It was found out that there is an optimal power stage bias current of 20 mA for lowest distortion. The THD of the proposed topology was simulated with the LTSpice simulator and measured with the audio spectrum analyzer U8903B from Keysight and by a simple solution using a handheld recorder and an integrated Digital to Analog Converter (DAC). The Keysight was able to measure −104.5 dB THD_R, whereas simple solution did measure −92.8 dB.

Keywords: audio amplifier; feedback loop; transistor pair; THD

Avdio ojačevalnik z nizkim popačenjem

Izvleček: Članek predstavlja načrtovanje in izvedbo visokokvalitetnega avdio ojačevalnika. Načrt je preprost in lahko doseže zelo nizka harmonska popačenja (THD), pod −100 dB za namizne zvočnike z močmi do 10 W. Rešitev za doseganje nizkih popačenj so tranzistorski pari skupaj s preprosto topologijo, ki v izhodni stopnji ne zahteva tranzistorjev z enakimi lastnostmi. Vhodna in izhodna stopnja sta bili analizirani pri različnih delovnih tokovih. Ugotovljeno je bilo, da obstaja optimalni delovni tok 20 mA za doseganje najmanjšega popačenja. THD predlagane topologije je bil analiziran v programu LTSpice in pomerjen z avdio spektralnim analizatorjem Keysight U8903B ter z uporabo ročnega diktafona in integriranega digitalno-analognega pretvornika. Z uporabo Keysight inštrumenta se je izmerilo −104.5 dB THD_R, z enostavno rešitvijo pa −92.8 dB.

Ključne besede: avdio ojačevalnik; povratna zanka; tranzistorski par; THD

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1 Introduction

Audio amplifiers have three main parameters, that are important for listening experience. The first one is **power**. This parameter is important if the speakers will be used for music playback. In home speaker setup people would rarely need sound power in excess of 100 W, whereas in concert halls the power of amplifier systems needs to exceed 10 kW [1].

The second parameter is **Total Harmonic Distortion** (THD). It presents main signal quality characteristics combined in one parameter. The main quality parameters are linearity, slew rate, overshoot and stability.

And third, the **Signal to Noise Ratio** (SNR). This is another quality parameter that compares the audio signal power and the noise power. Because harmonic distortion is counted as a part of the noise in signal, it is included in SNR calculation.

In the paper it was decided to optimize distortion parameter, as it has the biggest impact on the quality and timbre of the amplificated signal. A signal with lower THD offers more music details and higher quality real-life listening experience.

At the beginning, research of audio amplifier market was done, which offers a lot of different audio systems. Many of them are implemented using standard Integrated Circuit (IC) amplifiers and are advertised to be superior without specifying any objective data with the following quotes: *The Way The Artists Truly In-*

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tended, *Purer sound*, *Shut out the noise*, *Wide frequency response for ultra-clear harmonics, etc.* [2]. On the other hand, there are many audiophile amplifiers that specify at least basic amplifier quality numbers (THD, Signal to Noise Ratio (SNR), Crosstalk…) but are significantly more expensive and sometimes they don't offer better performance as cheaper integrated circuit solutions.

A few commonly known audio amplifiers are compared in Table 1. The IC solutions have the worst performance, with the exception of LM3886 that is better than affordable medium class amplifiers from reputable companies Onkyo and Marantz. If a premium quality amplifier is chosen, such as Luxman or Classe Delta Mono, a price rises up to 10,000 € and more.

The development of the proposed high-quality amplifier was done under Master thesis [11], with budget accessible components.

2 Available circuit schematic performance analysis

In the proposed design, bipolar transistors are used for multiple reasons. They are popular in discrete analog circuits, and they have faster and better phase margin because of lower input capacitance compared to MOS transistors. The low input biasing voltage of bipolar transistors increases the swing of output signal to use more supply voltage range and higher current gains call for less components in design. A crucial component for high quality amplifier design with discrete components is the precise transistor pair that is available in the standalone package and can be used for a precise differential input stage formation, assembly of current mirrors, logarithmic amplifiers, etc., which is suitable for the proposed solution. Different topologies from the simplest to the more complex ones were analyzed to find the most suitable solution. These topologies consist of classic amplifier Classes [12]: A, B and AB. Additionally, one of high-quality amplifiers, designed by Linsley Hood in 1969 [13], was studied and analyzed. The design is presented in the next chapter, along with an operational amplifier LM2904 [14].

2.1 Linsley hood simple amplifier (Class AB)

Linsley Hood has published a very simple design with a good performance (THD less than –60 dB) in the magazine Wireless World [13]. Therefore, it is a great candidate for future analysis and to be used as building block for better and more complex architectures. A more thorough description of the simple output stage which uses 2 NPN transistors and was used in the proposed design is described in following chapter.

In Linsley's design, shown in Figure 1, a single PNP transistor (Q33) was used for an input stage and feedback from the output. An NPN transistor Q34 was used for the voltage amplification. The output stage was implemented with a double NPN stage (Q35 and Q36). As the output transistors are the same type (NPN), the matching that is necessary for a classical output stage with NPN and PNP is not needed, since the parameters are very similar between the same type of transistors.

Amplifier was analyzed at signal voltage nodes (N1, N2, N3, N4, Vin, Vout) at different output stage bias currents

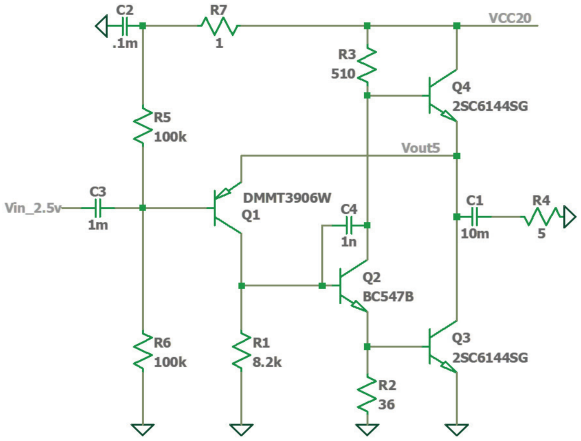

Figure 1: Linsley Hood amplifier simulation design

Table 1: Comparison of some audio amplifiers on the market

Amplifier	THD at 1 kHz [dB]	THD in FS [dB]	PRICE [€]	PRICE [Source]
TI LM4950 (IC) [3]	–55 (5 W, 8 Ω)	–45 (5 W, 8 Ω)	2.50	mouser.com
TI LM3886 (IC) [4]	–80 (30 W, 8 Ω)	–70 (30 W, 8 Ω)	7.66	mouser.com
TI TLV320AIC3268 (IC) [5]	–40 (1 W, 8 Ω)	/	9.49	mouser.com
Onkyo A9110 [6]	–66 (55 W, 8 Ω)	/	249.00	onkyo.com
Marantz PM6007 [7]	/	–62 (/)	640.00	marantz.com
Cambridge Audio Edge A [8]	–94 (100 W, 8 Ω)	–74 (100 W, 8 Ω)	5,999.00	md-sound.de
Luxman L-509x [9]	–83 (/, 8 Ω)	–64 (/, 8 Ω)	9,900.00	soundtemple.eu
Classe Delta Mono [10]	–106 (78 W, 8 Ω)	–96 (78 W, 8 Ω)	11,999.00	afmerate.com

(1 mA, 100 mA, 1.5 A) to see how they affect the performance. The bias is set by adjusting the resistor R40, which applies a bias current to the output transistor Q35.

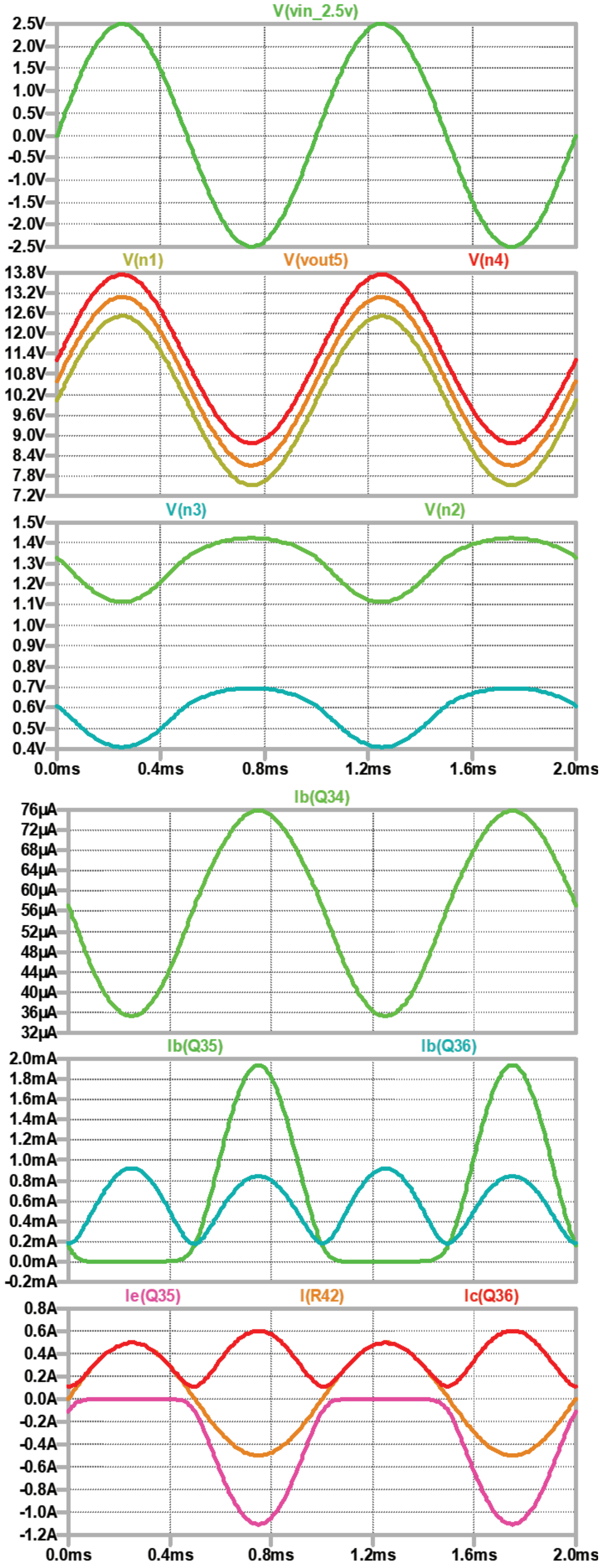

Figure 2: Voltage and current signals of a Class AB configuration (100 mA bias)

A 100 mA bias current was used for the Class AB output stage simulations which results are presented in Figure 2. In the circuit, there are 3 signals at nodes N1, Vout5 and N4 closely matching the input signal. They have offset defined by the transistor bias voltage which is approximately 0.7 V. The lowest voltage is at input of an amplifier (N1, base of transistor Q33) representing a non-inverting operational amplifier input. The output signal that drives speakers is marked with Vout5. This signal is also connected to an inverting input for a negative voltage feedback (emitter of transistor Q33). Another bias voltage higher is a signal driving base of the top output stage transistor (N4, Q36). The input transistor Q33 compensates the output signal (N2, collector Q33) to drive a voltage amplification transistor Q34, therefore signal N2 is not a perfect sine. The collector of Q34 (N4) then matches the sine and drives the upper output stage transistor Q36. The emitter of Q34 (N3) transfers the compensated signal to lower output stage transistor (Q35). The output signal matches input signal very closely with a distortion less than –60 dB, shown later in Table 3.

Looking at the currents of the output stage transistors Q35 and Q36, shown on bottom traces in Figure 2, explains the situation behind the compensated voltage signal. The compensation is needed because transistor Q35 is not always conducting, whereas Q36 needs to conduct current at negative and positive sine wave. The difference in output currents of Q35 and Q36 represents the current that drives the output speakers (R42). The base connections of output transistors are driven in anti-phase. The lower transistor is driven by node N3 and upper transistor by node N4.

It is important to note a time delay of voltage and current signals. If the delay becomes too big, the amplifier becomes unstable, therefore a proper phase compensation is needed. The main reason for delay is an influence of parasitic capacitances and inductances of PCB and components that shift voltage and current signals. The compensation is made with a capacitor and must be optimally chosen. If the compensation is weak, then feedback will respond too fast to the input signal change, and if the compensation is too strong, then feedback will not respond to the input signal fast enough.

A bias current of 1 mA was used for Class B output stage as seen in Figure 3. It can be noticed that some signals (N2, N3, N4, Ib(Q34)) have sharp response at zero crossing resulting in output distortion, shown in detail in Figure 5.

The sharp response is the result of a small output stage bias (1 mA). The input transistor therefore needs to quickly compensate it and it generates a very sharp output current that flows into base of Q34. An overshoot in regulation is inevitable and results in current spikes when output stage transistors Q35 and Q36 start to conduct.

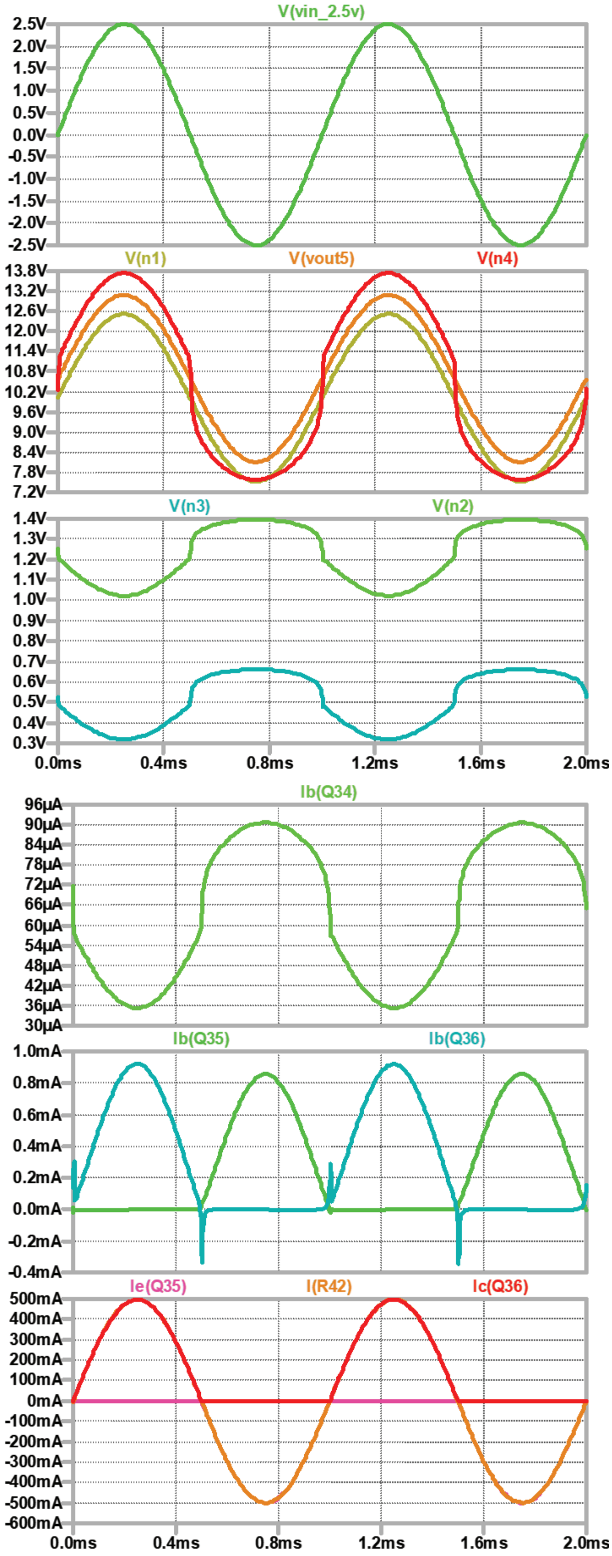

Figure 3: Voltage and current signals of a Class B configuration (1 mA bias)

Also, voltage signals of N1, N4 and Vout nodes are not correlated through the whole sine wave. The negative sine half of N4 node is distorted because feedback loop tries to correct the error in the output signal.

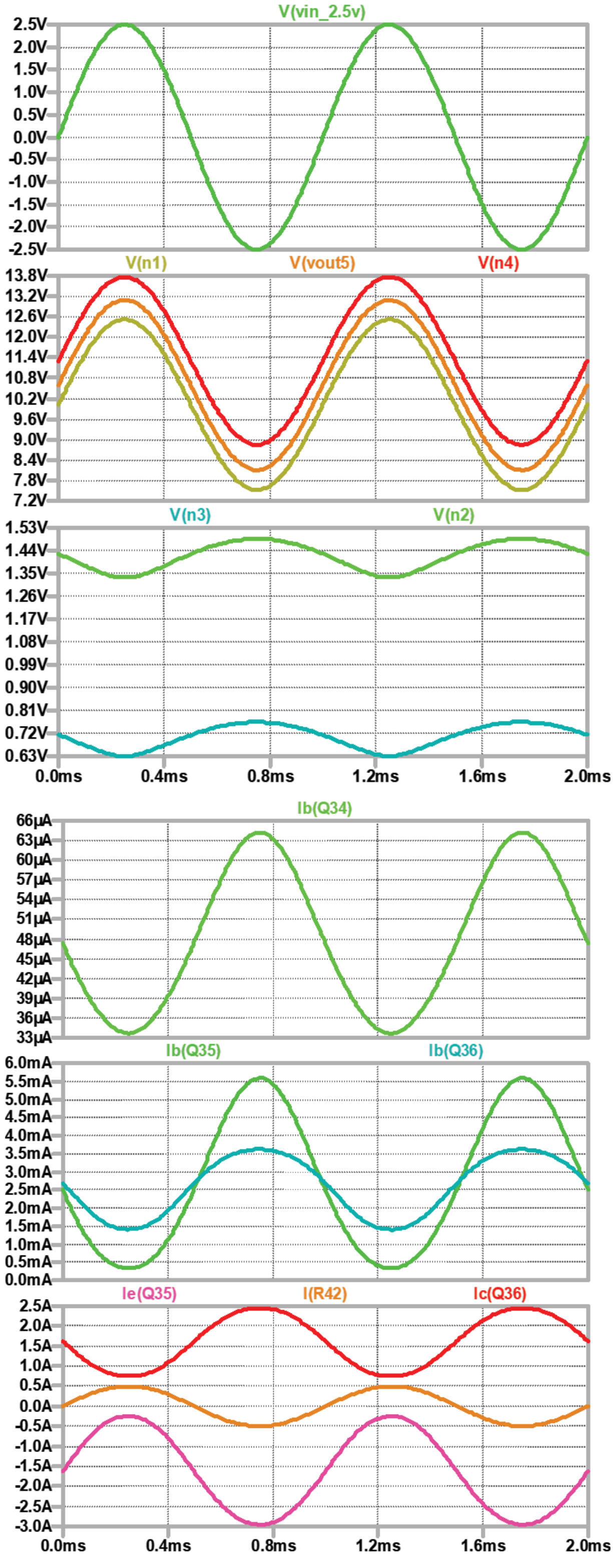

Figure 4: Voltage and current signals of a Class A configuration (1.5 A bias)

For the last simulation, a bias current of 1.5 A was used for a Class A output stage simulation, which results are shown in Figure 4. All signals are sinusoidal as transistors are always in the active region, therefore only a small correction is needed to compensate an exponential $U_{gate}(I_{emitter})$ transistor characteristic. The correction is done by negative feedback loop of the input transistor Q33. The output transistor currents graph shows why a Class A design is not appropriate as both transistors conduct 1.5 A in quiescence. When applying a signal that changes the load current from –500 mA to 500 mA, the current consumption of the output stage is in the from 500 mA to 3.0 A, showing the inefficiency of a Class A topology.

A THD of different amplifier classes were also simulated and are presented in the following chapters.

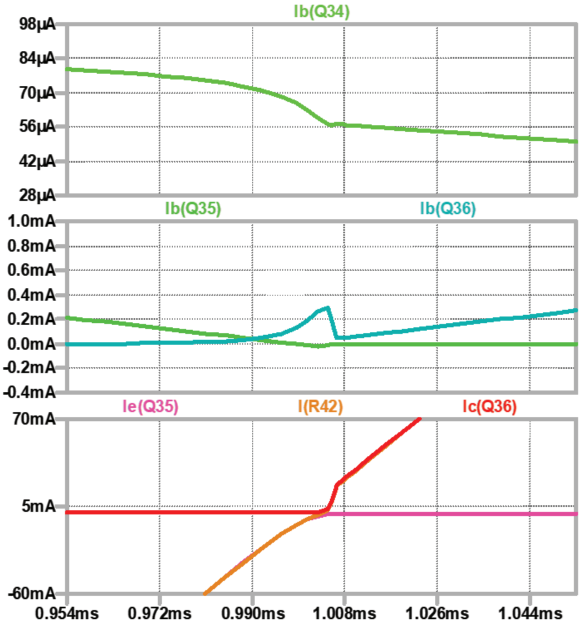

Figure 5: Sharp response at zero crossing with a Class B (1 mA bias)

2.2 Industrial grade off-the-shelf operational amplifier LM2904 (Class AB)

The documentation of integrated circuits is an excellent source of quality and reliable circuit designs, although schematics of complete designs are omitted nowadays. One of reliable integrated solution with included simplified schematic is LM2904 operational amplifier [14]. The design is simple and robust with predictable stability. The schematics of LM2904 is presented in Figure 6.

The input stage consists of the differential input stage using PNP transistors (Q1, Q2, Q3, Q4) biased with current mirrors. For additional amplification and lower input currents the input stage consists of transistors connected in a Darlington configuration.

The second stage (Q10, Q11) has relatively high input impedance, not to distort the signal, and amplifies current from the input stage. For better output utilization, 2 transistors, NPN and PNP, are used in common collector configuration therefore cancelling out the 0.7 V bias voltage of this stage.

The signal from the second stage is feed to the voltage amplification stage (Q12) with a 100 µA bias current.

For the final stage, NPN and PNP transistors (Q6, Q13) are used. For higher current capability the upper output transistor (Q6) is additionally amplified, using transistor Q5 in Darlington configuration. A current protection is done with a shunt resistor (R_{SC}), connected to a gate of transistor (Q7).

The main part of the LM2904 circuit used in the proposed design, is the input differential pair. Performed analysis and comparison of input stages of Linsley's amplifier and LM2904 are presented in the next chapter. The Linsley's input stage was analyzed in Linsley's amplifier circuit and simplified LM2904 input stage without Darlington connection for additional amplification was analyzed in proposed design, show in Figure 7.

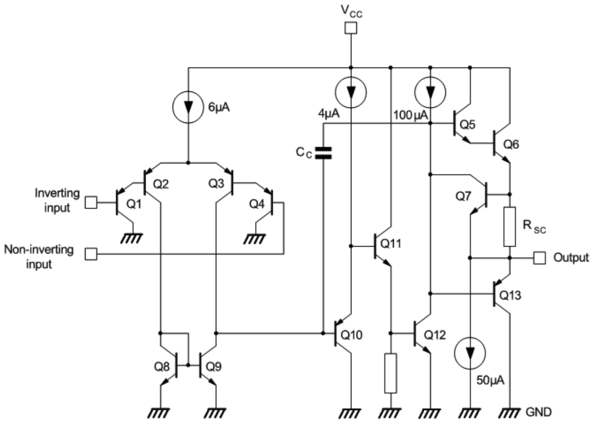

Figure 6: A simplified schematics of LM2904 operational amplifier

2.3 The proposed design (Class AB)

The base of the proposed design presents the LM2904 transistor differential pair input stage, together with a double NPN output stage from the Linsley Hood's amplifier. Between input and output stages, additional components were used to shorten signal path, lower distortion and speed up the feedback path. The schematic of the proposed design is shown in Figure 7.

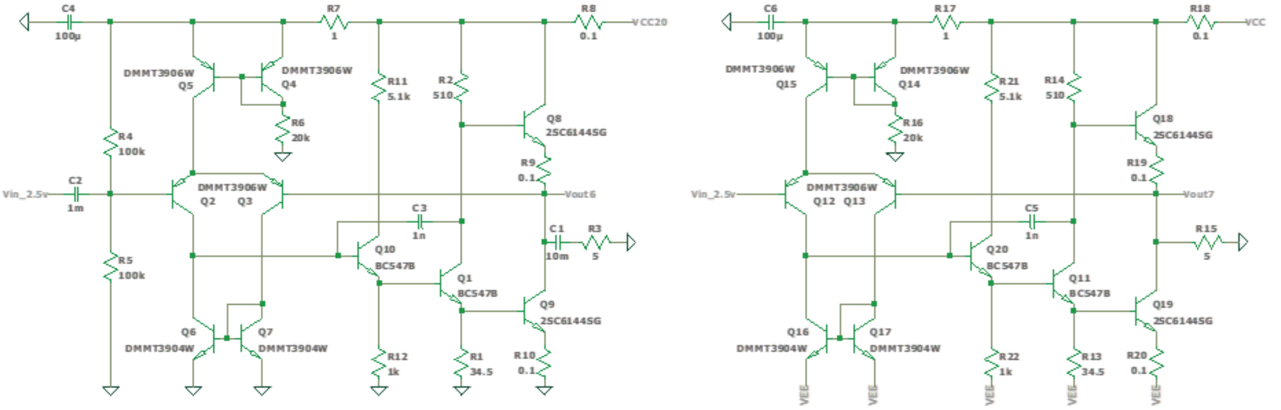

Figure 7: Simulation schematics of proposed amplifier (single supply LEFT, dual supply RIGHT)

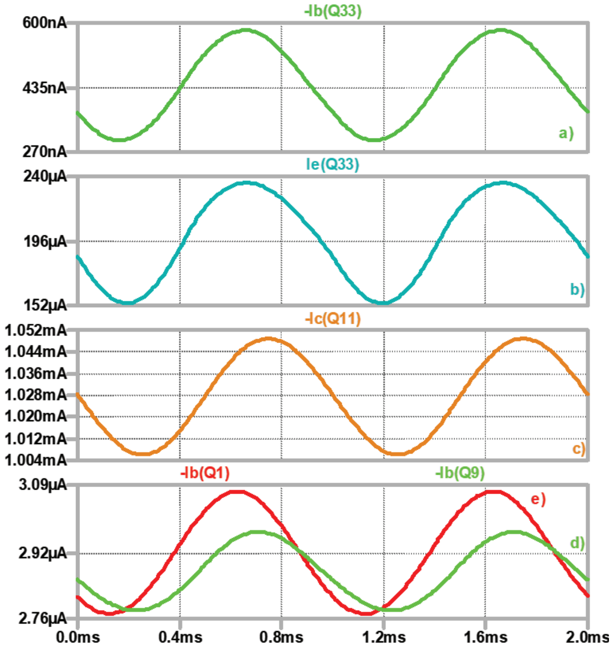

Figure 8: Single vs differential input stage: a) input current into base of single stage, b) current into emitter of single stage, c) current of differential stage, d) inverting differential input stage base current, e) non-inverting differential input stage base current

A signal propagation comparison was made between Linsley Hood single transistor input stage (IS) and differential input stage in the proposed design. The amplifiers' simulation schematics are shown in Figure 1 and Figure 7. The input stage currents (Figure 8) are consisting of DC bias and AC signal.

Interestingly, the base input (Figure 8a) and emitter (Figure 8b) bias currents of single input stage were lower than the differential stage (Figure 8c, e) by 2.5 µA and 0.8 mA. Also, the phase shift of signals is smaller in single IS compared to the differential IS. Despite lower values, the THD was higher in a single input stage of Linsley Hood.

To clarify the issue, Fast Fourier Transform (FFT) analysis was performed at different input stage bias currents. A signal of 1 kHz at 2.5 V amplitude was used for excitation. The bias current did not affect Linsley Hood's amplifier input stage and the second harmonic caused approximate –70 dB distortion, whereas the proposed design with differential input stage, is affected by the input stage bias current – the higher it is, the lower is the distortion. In the proposed design, when the bias current is over 1 mA, the 2nd harmonic decreases, but the 3rd harmonic increases. At 2 mA bias current, the 3rd harmonic is at –94.5 dB and the second at –99.2 dB, showing that this is an optimal relation between supplied bias current and distortion. The bias current comparison results are shown in Table 2.

3 THD simulation of proposed design

Simulations of THD were performed in LTSpice, which is a simple and powerful Spice based program with Graphical User Interface (GUI). All previously mentioned topologies were analyzed to get a good understanding of the circuit operation. The THD was measured by 1 kHz, 5 V sine wave excitation on input. The FFT analysis result of proposed design (topology 11 in Table 3) is shown in Figure 9.

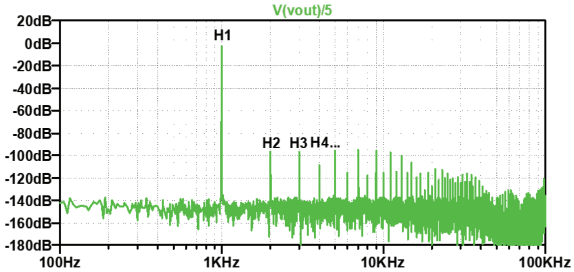

Figure 9: FFT analysis results of proposed design

Table 2: 2nd harmonic comparison between Linsley Hood and the proposed amplifier input stage

	Fundamental to 2. harmonic ratio [dB] (IS bias resistor [kΩ])					
IS bias current [uA]	100	200	500	1000	2000	5000
Linsley	−67.5 (30)	−70.2 (9)	−70.8 (3)	−71.0 (1.4)	−70.7 (0.66)	−70.2 (0.26)
Proposed	−75.7 (200)	−81.8 (100)	−89.4 (41)	−95.0 (20)	−99.2 (10)	−102.2 (4)

Table 3: Harmonic amplitudes at 5 Ω load and 5 V amplitude of in/out signal

Topology		Harmonic [dB]				Bias current of output stage [A]
		2.	3.	4.	5.	
1	MOS follower 6k/10k	−43.1	−48.5	−53.1	−57.6	2.0
2	BJT follower 2.8k	−38.7	−40.6	−42.7	−44.6	2.0
3	BJT follower 2k	−56.0	−61.2	−70.9	−76.1	2.3
4	BJT follower 430	−77.5	−70.6	−90.7	−105.5	10.0, 1 ΩLOAD
5	BJT Class B	−43.4	−24.0	−44.9	−29.2	0.0
6	BJT Class AB 5mA, 2k	−49.9	−65.0	−76.8	−70.2	100 m
7	Linsley Hood AB	−66.1	−79.5	−89.2	−93.8	100 m
8	Linsley Hood B	−67.8	−63.7	−66.1	−63.0	1 m
9	Linsley Hood A	−69.4	−72.4	−79.2	−94.1	2.0
10	Proposed with only + supply	−92.9	−94.3	−106.9	−92.6	100 m
11	Proposed with ± supply	−94.1	−94.2	−106.4	−92.7	100 m

The higher harmonics from the FFT analysis plot were compared with the fundamental tone H1. In Table 3, results for individual harmonic distortion and bias currents are presented. Cells with the worst harmonics are shaded. The performance of Linsley Hood's amplifier and proposed design is shown alongside with basic topologies consisting of single or dual transistors (topologies 1 – 6). The basic topologies are included to show a distortion which is caused by transistor's nonlinear characteristic and an influence of feedback to linearization.

With a simple voltage follower topology (topologies 1 - 4), the amplification quality is solely dependent of a single transistor characteristic. The main transfer characteristic is $I_{OUT}(U_{IN})$. The transistor models used are Infineon BSB012N03LX3 for MOSFET and Onsemi 2SC6144SG for BJT. At 2 A bias current, a BJT transistor had worse distortion as MOSFET by 4.4 dB (−43.1, −38.7 dB). By slight bias current raise to 2.3 A, the BJT distortion was greatly improved to −56.0 dB. In simulation, the bias was increased to unrealistic value 10 A, where a single BJT transistor has distortion −70.6 dB and it could compete with quality amplifiers.

A Class B topology, without feedback (topology 5), has the worst distortion. The odd harmonics contribute most to the distortion, with third being the worst at −24.0 dB. It was found that the THD improves by increasing input signal levels. This is because transistors stay less time in a non-conducting region, therefore the signal is less distorted.

By adding a small bias current through output transistors, the distortion can be lowered (topology 6). Class AB with 100 mA bias, has −49.9 dB distortion at 5 mA voltage amplification stage bias current.

The THD also improves when simple feedback with one transistor is used which is utilized in the Linsley Hood design (topologies 7-9). The distortion from an ordinary AB stage is decreased by 16.2 dB to −66.1 dB. A distortion of Class B amplifier can also be decreased with feedback. A Linsley Hood amplifier in Class B therefore performs 39.0 dB better than a simple Class B amplifier (−24.0, −63.0 dB).

The proposed design achieved the lowest distortion around −92.6 dB, if supplied with a single (positive) or dual (positive and negative) supply voltages (topologies 10, 11). Using dual supply voltages is preferred to omit small signal and power coupling capacitors which realize middle voltage level. The usage of coupling capacitors is not desired because real capacitors have many parasitic elements, occupy space on a PCB and add additional phase delay which affects signal distortion.

4 Measurements

The schematics and PCB of the circuit were drawn in Altium Designer. All appropriate power supplies, isolation, D/A converter and pre-amplification stage were also included on the PCB, as the proposed design (Figure 7 RIGHT) is used in a complete audio amplifier and marked as R AMPLIFIER and L AMPLIFIER in a block schematic of Figure 10.

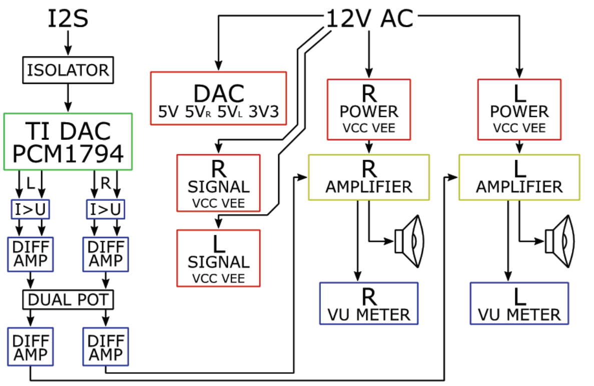

Figure 10: Block schematics of complete circuit with including proposed amplifier

The connection between pre-amplification stage and proposed amplifier was done differentially to limit the noise coupling from an environment. The output signal and ground reference signal from a block DIFF AMP were connected through a twisted pair cable to an input of the amplifier and ground. The connection is summarized in Figure 11. On a PCB circuit, a star connection for ground signals was used as close to the load ground connection as possible shown on Figure 12. Star connection lowers the noise coupling and ensures proper signal integrity.

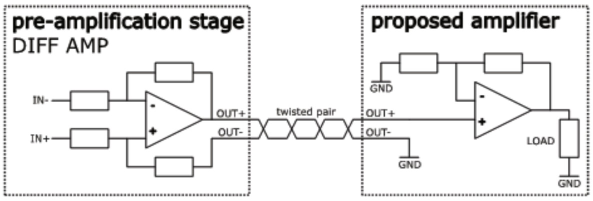

Figure 11: Connection between pre-amplifier and proposed amplifier

The distortion of a proposed design was measured using an industry standard Audio Spectrum Analyzer U8903B from Keysight [15]. A measurement of THD_R and SINAD (Signal to Noise and Distortion) were made at multiple frequencies and amplitudes. A power stage bias was also measured.

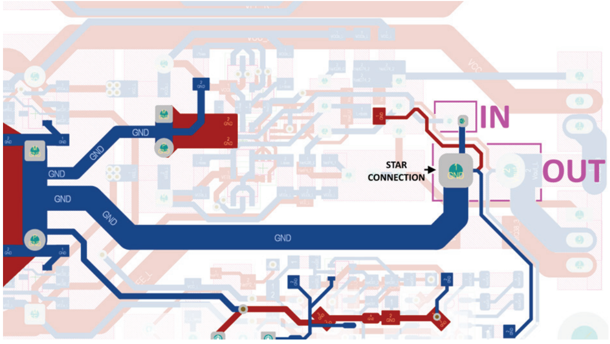

Figure 12: Star connection for ground signal nodes at load output connector of proposed amplifier

Initially, power was supplied with a transformer from an AC grid and rectified on the circuit, but this resulted in a poor SINAD characteristic in the range of 65 dB. To improve this, a 12 V battery supply was used and the SINAD improved to 75 dB.

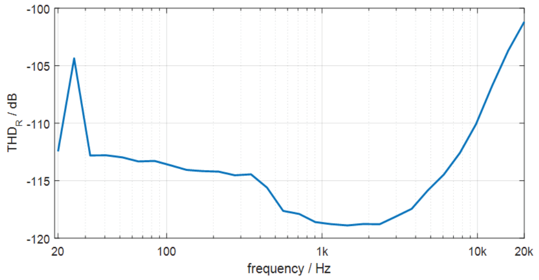

Figure 13: Keysight U8903B input-output characteristics

In Figure 13, an input-output characteristic of an audio spectrum analyzer was measured to set a reference value. The instrument's THD_R is around −100 dB to −120 dB with 50 Hz line noise.

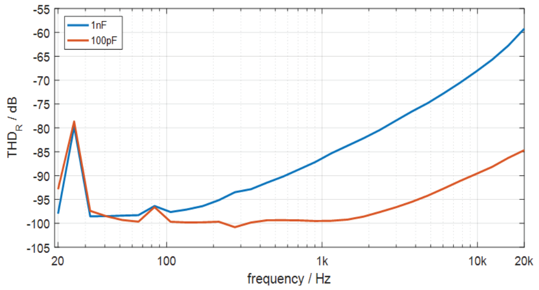

Figure 14: Influence of feedback capacitance

The proposed amplifier was measured using two different compensations in the feedback – 100 pF and 1 nF. The same compensation was used on power stage transistors due to their high bandwidth. It was found that decreasing compensation greatly improves THD_R at higher frequencies by 25 dB. In the region below

1 kHz, the THD_R is even better than simulated where it surpasses –100 dB. The results of measurements are presented in Figure 14.

A distortion comparison was made also with Linsley Hood's design and quality integrated headphone amplifier TI TPA6120A2 and results are shown in Figure 15. The Linsley's design did not perform as good as the proposed design, reaching THD_R around –50 dB. At higher frequencies distortion worsens because of low-cost capacitors used for DC component decoupling. The integrated headphone amplifier also did not perform as good as the proposed design with THD_R around –80 dB to –90 dB, except at higher frequencies where distortion improved under –100 dB. The circuit board and other used elements introduced a frequency pole nearby 10 kHz which resulted in a better THD_R.

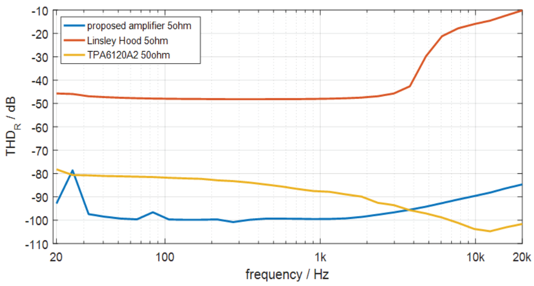

Figure 15: Frequency characteristics at 2 V_{RMS} input

A bias current in the output stage has also impact on the THD_R. A constant sine wave was used as the input and the bias current through output transistors was changed using potentiometer. In Table 4, results of distortion measurements are presented, where it can be found that the highest bias current does not necessarily mean the lowest THD_R. Instead, when bias currents are in the range from 20 to 40 mA, a signal with lowest distortion –108.4 dB was measured.

Biasing is influenced by the temperature of the transistors. The higher temperature will shift the $I_C(U_{BE})$ characteristic up, meaning that the same voltage bias will result in a higher current flow through a transistor. Temperature effect on bias was therefore canceled out by adjusting the bias to precise value before measuring the THD. Despite this, a difference of THD between measurements could be observed at the same bias current. This is due to a different temperature of output transistors between measurements. The current bias was adjusted in a sequence listed in Table 4 – from 4 mA to 320 mA to 5 mA. Consequently, the temperature of transistors before 320 mA measurement was lower than after the 320 mA measurement at the same current bias.

Amplifier was also characterized with and without a load. Results are shown in Figure 16. The THD_R difference is 5 dB. The reason is in higher currents needed for load driving; therefore a higher influence of transistor nonlinearities is present.

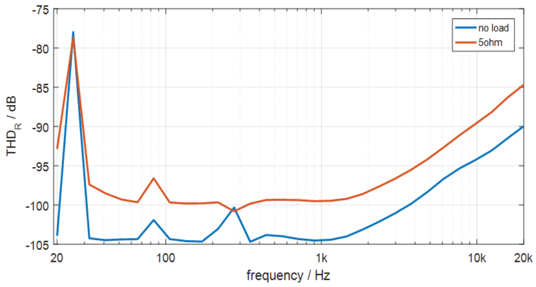

Figure 16: Frequency response of proposed amplifier at different loads

For measurement comparison, a simple and low-cost method for THD_R measurement was used as shown in Figure 17. An integrated high quality DA converter PCM1794 with best case scenario –108 dB THD_R was used as a signal generator. The DA needs a simple pre-amplifying stage that was made using TI operational amplifiers OPA1678 [16] with THD_R of –120 dB. The THD_R at 1 kHz was measured with a handheld voice recorder Tascam DR-22WL which uses a Cirrus Logic CS42L52 [17] codec with –88 dB THD_R. A final THD_R value was obtained from a recorded WAV file with FFT analysis performed within MATLAB program. In the measuring setup, the recorder has the worst distortion so a distortion of –88 dB was expected.

Despite the previous fact, total distortion of –92.8 dB was measured meaning some deviations from the circuit documentation exists. The control measurement was done with the Keysight equipment and a THD_R of –104.5 dB was obtained. Results show that the simple method is not suitable for measuring the distortion of

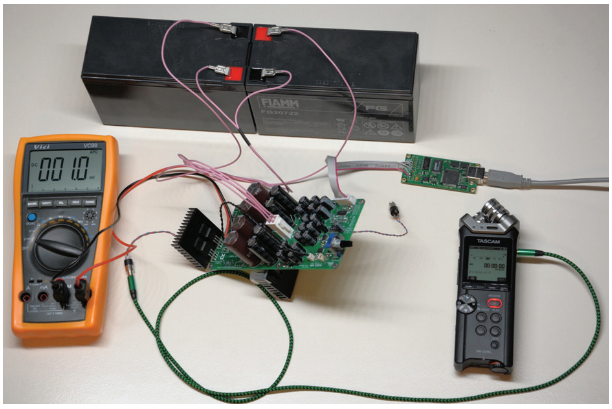

Figure 17: A simple and low-cost method for measuring THD_R

Table 4: Distortion at 440 Hz, 2 V_{RMS} input signal

Bias current with signal [mA]	4	10	20	40	80	160	320	160	80	40	20	10	5
THD [dB]	-98.3	-102.0	-108.0	-107.3	-105.6	-103.7	-102.5	-103.8	-106.4	-107.7	-108.4	-105.0	-100.2

proposed amplifier, as a distortion of consumer recorders using off-the-shelf codecs are decades worse than a high-fidelity audio equipment. The measurement results of this comparison are shown in Figure 18.

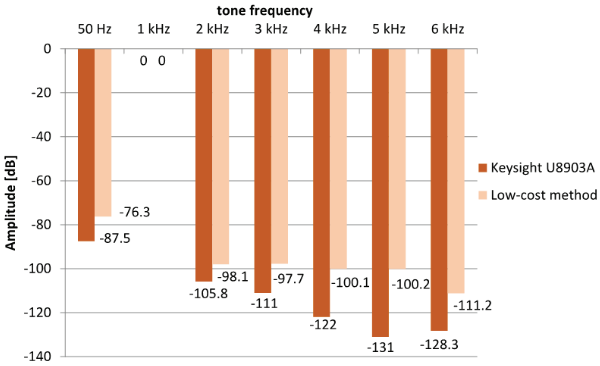

Figure 18: Comparison of harmonics and 50 Hz distortion on proposed amplifier output

5 Conclusions

The paper presents that a high-quality amplifier can be realized using simple schematics and affordable components. The proposed amplifier exceeded –100 dB THD_R. Further feedback transfer function characterization would allow additional compensation optimization, which would result in distortion improvement.

Although the analog amplifier distortion can be additionally improved, firstly the input signal must be improved to higher quality. A noise improvement would also be needed as the noise level is much higher (around 75 dB) than distortion.

The problem is also how to obtain recorded music with –100 dB distortion. All the recording equipment must have low noise and distortion. The recordings must not be poorly compressed and must have lossless quality. Also, the room in which the music is played must have low noise floor to fully enjoy the quality.

All the above is hard to achieve, and yet the total noise and distortion using the proposed design is better than an average consumer amplifier and contributes to an excellent listening experience with a simple design.

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7 Conflict of interest

The authors confirm there are no conflicts of interests in connection to the work presented.

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