superLinear power amplifier

Architecture and Technology

The basic architecture of *superLinear* amplifiers with mixed Feed-Back and Feed-Forward Error and Distortion Correction is reported in figure 1 below. The main functional blocks are shown:

- the main power amplifier (**MPA**), which provides the signal power to the load and defines the *temperament* of the overall amplifier;
- the auxiliary amplifier (**AuxA**), which has the role to generate and apply into the load loop a perfect anti-phase copy of the already low MPA distortion in order to fully cancel it and to achieve extremely high distortion performance of the overall power amplifier;
- within the AuxA block, two inner blocks are also shown: the distortion extractor (**EA**), which senses and extract the error-distortion components of MPA and the anti-phase error injector (**AEI**), which has the function to fine tune and align the anti-phase MPA distortion copy in order reach the highest possible levels of MPA distortion cancellation.

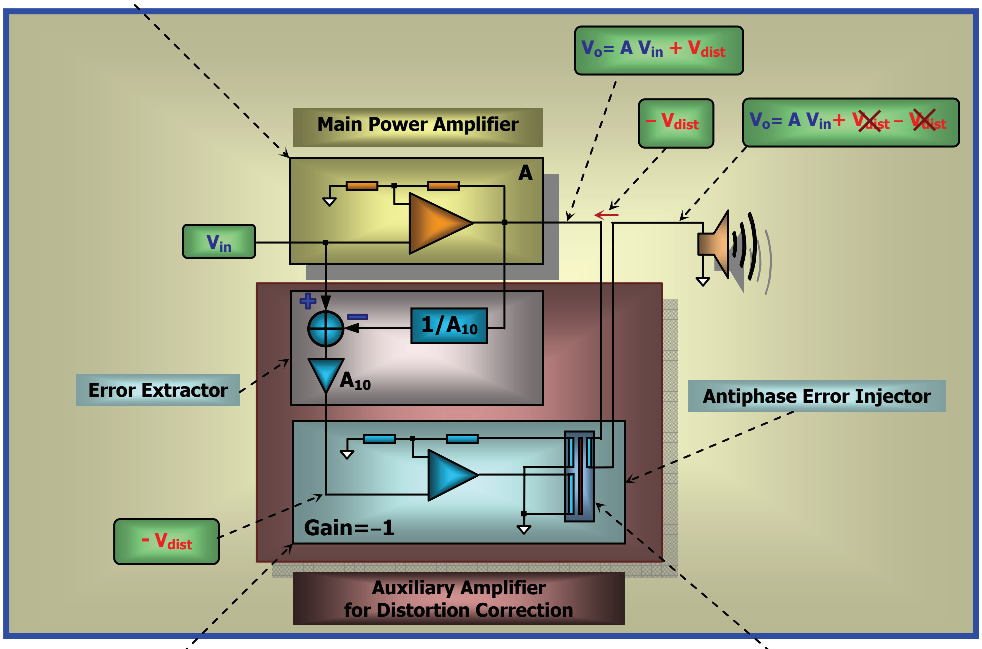
MPA. In the main power amplifier (MPA) which provides the signal power to the load, only **negative feedback** is employed, in its **standard** or in its **balanced** (**BEF**) form (see ref. **[1]** and **[2]**), which when appropriately applied can ensure the achievement of most of the design objective:

- very good gain stability, both in magnitude and phase, from DC to above 200kHz;
- low offset voltage and offset voltage drift;
- wide signal bandwidth with low gain and phase variations in the entire audio bandwidth;
- high and symmetrical positive and negative Slew-Rate and wide Power Bandwidth (PBW);
- high level of audio signal transparency and integrity;
- fairly good THD and IMD distortion performance, which are better than 0.02% and 0.001%, respectively, in the entire audio bandwidth.

AuxA. The **auxiliary amplifier** (AuxA) shown in Figure 1, is introduced into the *superLinear* architecture with the specific mission to virtually cancel the residual distortion of the main power amplifier, by utilizing a unique and very effective (patented) implementation of **Black's Feed-Forward Error Correction principle** (see ref. **[3], [4]**and **[5]**).

AuxA: the error and distortion extractor block. The error and distortion extraction is accomplished by means of a (usually passive) network whose role is to sense-detect the error and distortion component V_{dist} at the output of the main amplifier, and to separate it from the audio signal component $V_{o\text{-}sign}$. This task is carried out accurately in a very wide frequency bandwidth.

The main power amplifier (MPA) is designed to provide maximum **sonic transparency**. It operates in **class AB** and exploits **standard feed-back** and/or **balanced error feed-back (BEF) distortion correction** to achieve high levels of signal transparency (wideband and high speed) and to reduce distortion residue to **less than 0.02%** in the whole audio frequency band and at all power levels. **MPA voltage gain = A**.



The auxiliary amplifier (AuxA) corrects the residual error of the main power amplifier by means of a (**patented**) **feed-forward error correction** technique, the heart of which is a small output transformer with **magnetic flux cancellation** [size: 20(H) x 30 (D) mm]. It operates in **class A** and is able to cut all residual distortion components of the main power amplifier by a **factor of 300 (50 dB)** in a frequency range extending from 10 Hz up to 100kHz. **AuxA voltage gain = -1.**

Wideband **ferrite**-core toroidal transformer (5Hz-10MHz) for **distortion cancellation**

Fig. 1. Basic architecture of the Feed-Forward *superLinear* power amplifiers.

AuxA: the anti-phase error injector (AEI). The anti-phase error injector (**AEI**) has the function to generate a fine-tuned and aligned anti-phase copy of the MPA distortion so as to reach the highest possible level of MPA distortion cancellation ratio. With a good alignment, a distortion performance improvement up to 40-50 dB (i.e. 100-300 times) can be actually achieved. In fact the **measured worst case THD and IMD performance after the application of feed-forward distortion cancellation, is better than 0.0005% and 0.0001%**, respectively.

The feed-forward distortion cancellation mechanism. The basic flow of operations behind FFEC technique can be better understood if we refer to the simplified but more detailed schematic diagram of Figure 2. The output voltage of the main amplifier is given by $\mathbf{V_o}=\mathbf{V_{o\text{-}sign}}+\mathbf{V_{dist}}$ and contains the *wanted* amplified input voltage $\mathbf{V_{o\text{-}sign}}=\mathbf{AV_{in\text{-}sign}}$, where **A** is the voltage gain of the main power amplifier (MPA), plus its *undesired* but *unavoidable* distortion contribution $\mathbf{V_{dist}}$.

The superior and unique characteristic of the *superLinear* amplifier is that this distortion contribution is fully cancelled before reaching the loudspeaker system.

This result is achieved by means of the auxiliary feed-forward error correction path, which has been introduced, as depicted in Figure 2, inside the superLinear amplifier architecture, alongside the main signal path and consists of the error extraction block (EE) and the anti-phase error injector block (AEI).

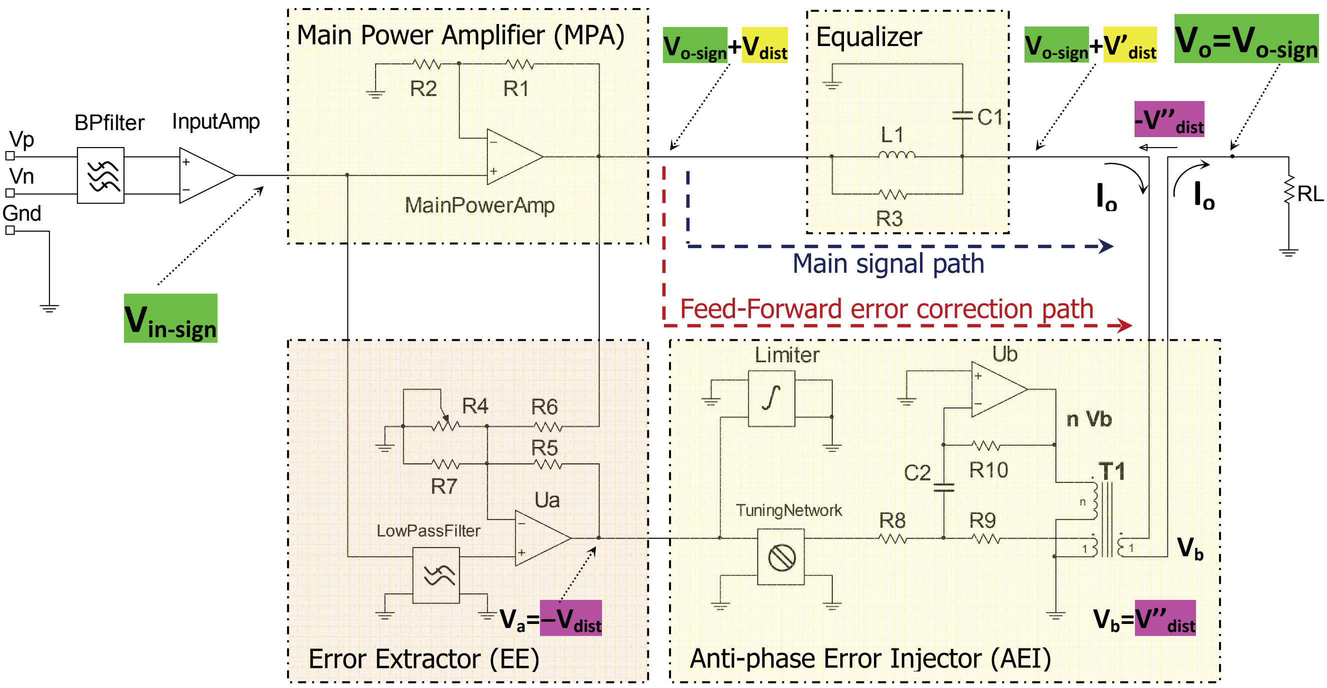


Fig. 2. Simplified circuit diagram of the *superLinear* power amplifier.

The distortion component $\mathbf{V_{dist}}$ is first detected and then separated from the main audio signal $\mathbf{AV_{in\text{-}sign}}$ by the Error Extractor block implemented with a single wideband (with unity gain frequency f_U=80MHz) low-noise and low-distortion op-amp (Ua). This operation is accomplished by attenuating $\mathbf{V_o}$ by a factor exactly equal to $\mathbf{A_{10}}$ (fine-tuned via trimmer R4 in figure 2), i.e. the dc gain of MPA, and then comparing the output voltage $\mathbf{V_o/A_{10}}$ with the reference input voltage $\mathbf{V_{in\text{-}sign}}$. The key feature of this simple EA solution is that when the frequency response of the low pass filter in the Error Extractor block of Figure 2 in calibrated to perfectly match the frequency response of the cascade of MPA and the attenuator of the error extractor block, the output of this comparison process is exactly equal to the fraction $\mathbf{-V_{dist}/A_{10}}$ of the MPA distortion.
It is therefore enough to amplify this fraction by a wide bandwidth (say at least 1MHz, i.e. 50 times higher than 20kHz) signal voltage amplifier with gain equal to $\mathbf{A_{10}}$ and we achieve at the output of EE block a perfect and inverted copy of MPA distortion contribution, i.e. $\mathbf{V_a}=-\mathbf{V_{dist}}$, as shown in figure 2.

The role of the AEI block is then to invert the sign of V_a and process it in order to produce a **corrective distortion copy V''_{dist}** which is **perfectly aligned (in amplitude and phase)** with its main and original distortion companion V'_{dist} which leaves the equalizer block together with the main power audio signal. At this joint the two distortion components, i.e. V'_{dist} coming from the main signal path and its anti-phase copy V''_{dist} coming from the corresponding feed-forward path, turn up in series into the load loop and **combine** to fully cancel each other before reaching the load. What is more, in virtue of the circuit topology, **the effectiveness of this cancellation mechanism is completely independent of the actual value of the load (loudspeaker) impedance**.

The residual level of the actual distortion that reaches the loudspeaker, i.e. $V_{o\text{-}dist} = V'_{dist} - V''_{dist}$, depends on the **quality of the alignment of the feed-forward path**, which has to be very good from low frequency up to 100kHz at least if we want to cancel (i.e. to reduce by more than 40 dB) all most significant and disturbing harmonics and intermodulation products produced by the main power amplifier.

Unfortunately our problems are not finished here with the cancellation of the distortion due to the main power amplifier. The high degree of cancellation of all distortion components of the MPA we can achieve with the feed-forward error correction technique, must be necessarily accompanied by a correspondingly high degree of linearity and distortion performance of the entire correction circuit (the auxiliary amplifier) in all operating conditions, at all audio frequencies and output power levels.

This is not an easy task, since the auxiliary amplifier, with its feed-forward error correction (FFEC) *engine*, operates in a very hostile context, since it is called to provide extremely low yet very accurate corrective voltages on top of the very high signal voltage V_o and, most of all, to sustain at its output the very high load current I_o without unwelcome consequences and interferences.

In such contexts very powerful intermodulation mechanisms, difficult to counteract, are usually activated, which can compromise the effectiveness of the amplifier distortion performance improvement process. In the worst case, the distortion performance of the overall *corrected* amplifier ends up being even worse than the main power amplifier itself.

The FFEC solution adopted in the **superLinear amplifier** intrinsically offers the very high level of linearity and distortion performance needed to ensure really outstanding distortion performance of the overall amplifier at all frequencies and power levels, as well as in all operating conditions.

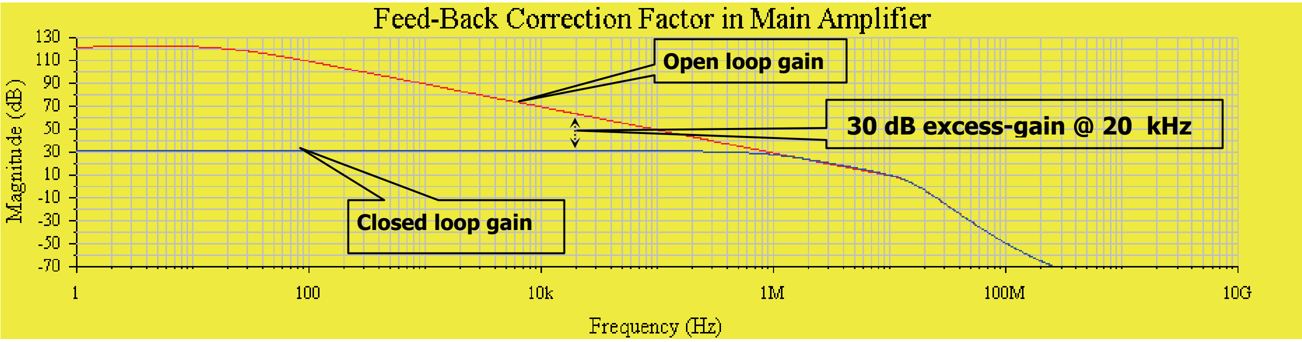
The ***heart*** of this solution is **the successful combination** (shown in Figure 2) of the **high-performance class A operated power op-amp** (**Ub)** with the **three winding wideband error-coupling transformer T1** (with a small-size **ferrite core**) appropriately inserted into the main feedback loop of the anti-phase error injector amplifier. In such a way the **magnetic flux produced in the ferrite core by the load current I_o** (which circulates in one of the secondary windings of T1 as well) can be **completely cancelled** and the main and very harmful low frequency intermodulation mechanisms usually associated with the use of magnetic transformers are **virtually neutralized.** This unique main flux cancellation feature allows to employ small-size cores (external diameter and height less than 30mm and 20mm, respectively), made from special high-permeability ferrites, for implementing very wide bandwidth transformers (from 5Hz to more than 10MHz), which can be effectively incorporated also in very high-power audio amplifier (with up to **40A** peak of rated output current).

The final results are as follows:

- a THD distortion performance of the entire FFEC circuit path better than **0.00005%** (i.e. 0.5ppm) can be stably achieved;
- the distortion performance of the overall amplifier fully depends on the actual level of the MPA distortion cancellation ratio achieved by the Feed-Forward Error Correction topology;

- the distortion performance of the overall FFEC corrected amplifier are extremely good with measured **THD** and **IMD** lower than **0.0005%** and **0.0001%**, respectively, at all frequencies and output power levels with a measurement bandwidth of **MBW=80kHz**.

Main simulated performances



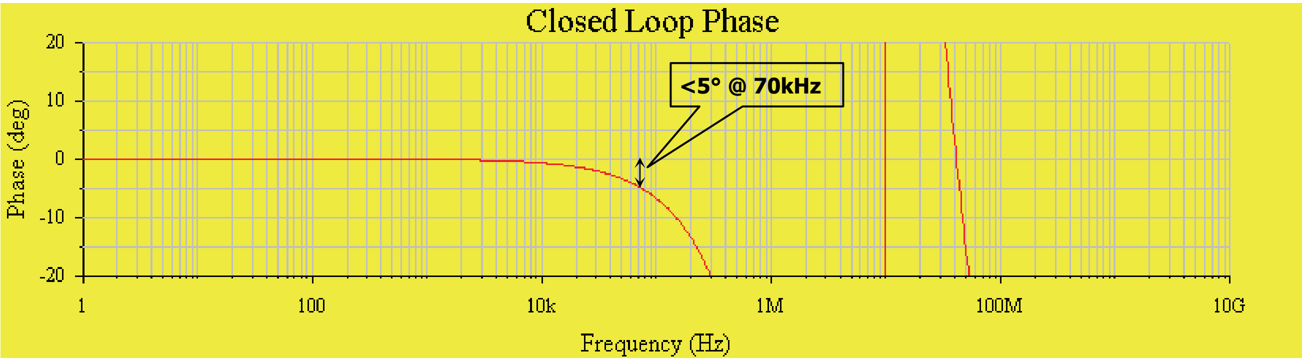


Fig. 3. Frequency response of the main power amplifier (magnitude and phase):
A. Closed loop bandwidth is more than 300kHz
B. Closed loop phase lag is less than 5 degrees up to 70kHz

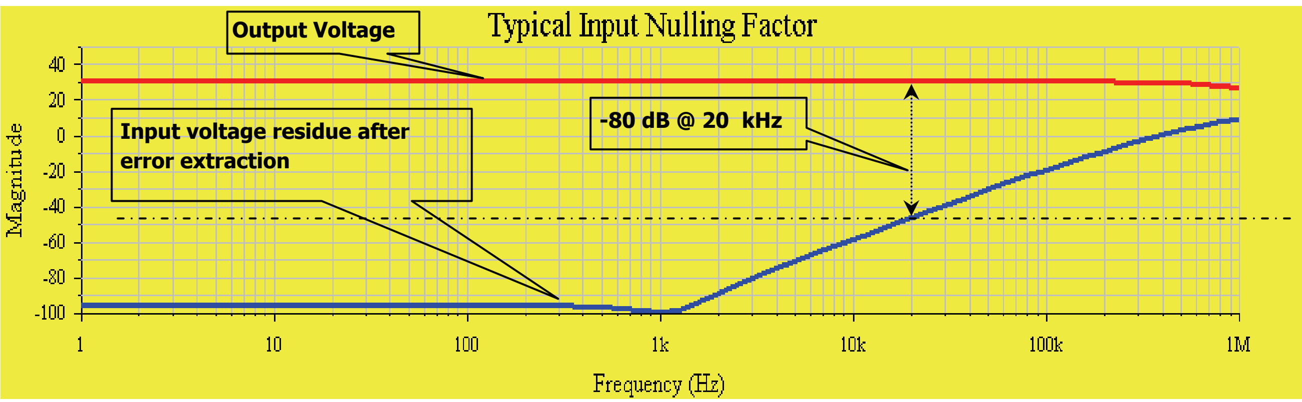


Fig. 4. Input signal residue is typically lower than 70 dB from 20 Hz to 30 kHz. This means a residue always lower than 10 mVrms at the maximum output voltage of 30 Vrms.

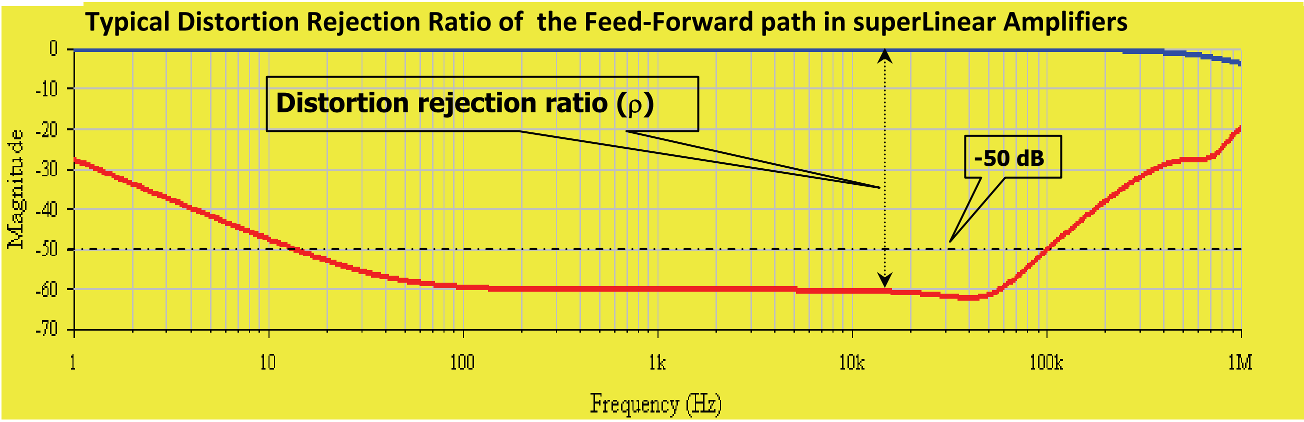


Fig. 5. Distortion rejection ratio (ρ) in superLinear power pmplifiers is more than 50 dB (= 300) from 20 Hz to 100 kHz, and more than 30 dB up to 300 kHz

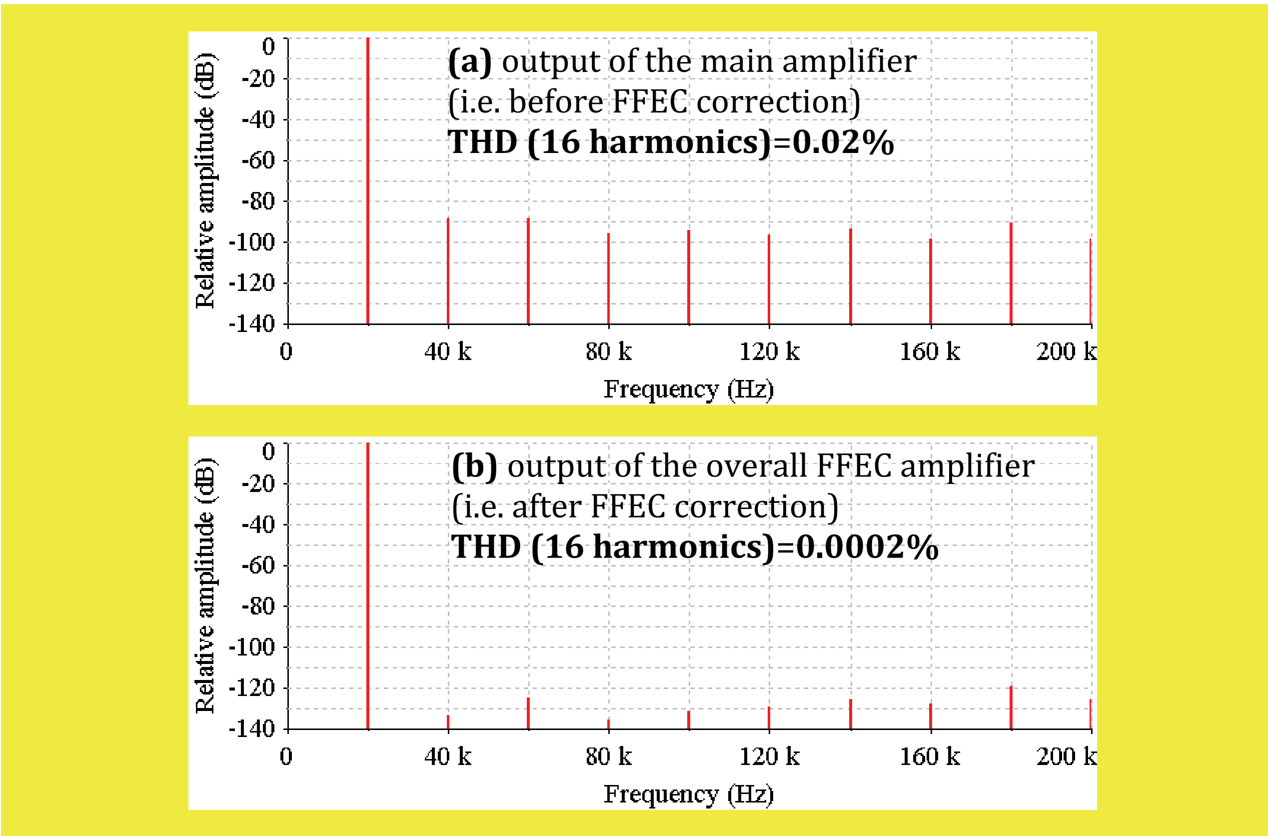


Fig. 6. Simulated typical frequency spectrum of the superLinear amplifier at 120 W into 8Ω. Fundamental frequency F_o=20 kHz.
(a): Frequency spectrum of the output voltage before FFEC correction
(b): Frequency spectrum of the output voltage after FFEC correction

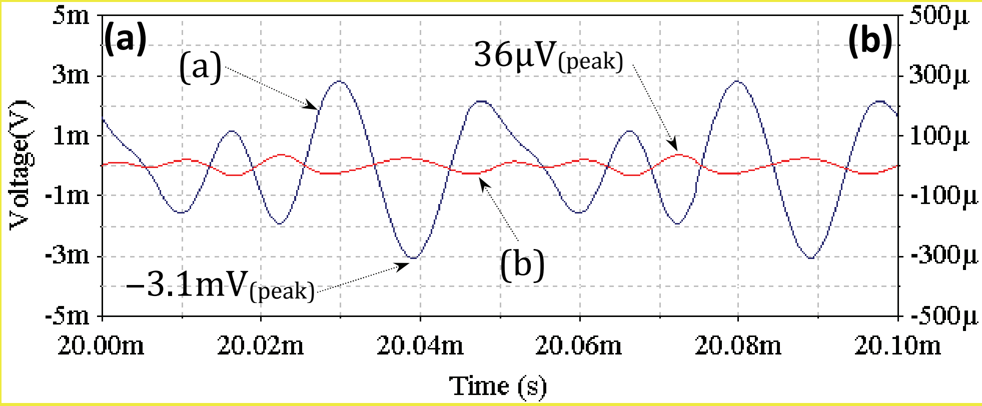


Fig. 7. Simulated distortion residue of the superLinear amplifier at 120 W into 8Ω. Fundamental frequency F_o=20 kHz. Post-process: a 20kHz Notch Filter followed by a 100kHz, 5th degree, Low-Pass filter (both with ideal op-amps) .

(a): Main power amplifier (before FFEC correction). Peak of distortion residue: –3.1mV
(b): Overall Amplifier (after FFEC correction). Peak of distortion residue: +36µV

Further readings

[1] G. Stochino, A. Pantaleoni, "*Amplifier Device With Reiterable Error Correction Scheme With Balanced Negative Feedback*", U.S. Patent N. 8,686,793, April 1, 2014

[2] G. Stochino, "*Investigations and developments related to feedback and feed-forward error correction-part 1*", Linear Audio, Vol.7, pp. 73-115

[3] G. Stochino, "*Audio Design Leaps Forward?*", Electronics World + Wireless World, Vol. 100, No. 1703, Oct. 1994, pp.818-827

[4] G. Stochino, S. Porrà, "*Audio Power Amplifier Apparatus*", US. Patent N. 7,564,304, July 21, 2009

[5] G. Stochino, "*Investigations and developments related to feedback and feed-forward error correction-part 2*", Linear Audio, Vol.9, pp. t.b.d.