Analysis of distortion sources in three-stage Class B audio power amplifiers

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Abstract: Audio power amplifiers (APAs) are essential for high-fidelity sound reproduction, requiring high linearity and low total harmonic distortion (THD). Three-stage Class B amplifier architectures are widely used due to their efficiency, simplicity, and high output power capability; however, achieving low distortion across the entire audio frequency range remains challenging. This paper presents an analysis of distortion mechanisms in a conventional three-stage Class B audio power amplifier comprising a differential input stage, a voltage amplifier stage, and a push-pull output stage. Seven major sources of distortion are identified and examined. The frequency dependence of THD is evaluated, showing minimal distortion at low frequencies and a significant increase at mid- and high-frequency ranges due to the interaction of multiple nonlinear effects. The results provide practical insights for improving linearity and reducing THD in Class B audio power amplifier design.

Keywords: audio power amplifier, total harmonic distortion, Class B amplifier, nonlinear distortion, feedback

INTRODUCTION

Audio power amplifiers (APAs) are fundamental components of high-fidelity audio systems, where strict requirements are imposed on signal linearity and total harmonic distortion (THD). Among the wide range of circuit topologies, three-stage Class B amplifier architectures are particularly popular due to their structural simplicity, high efficiency, and capability to deliver substantial output power. These advantages have led to their extensive use in both commercial and professional audio applications.

Despite their widespread adoption, achieving consistently low distortion across the entire audio frequency range remains a significant design challenge. This difficulty arises from the simultaneous presence and interaction of multiple nonlinear mechanisms within the amplifier structure. In three-stage Class B designs, distortion contributions originate not only from the output stage but also from the input differential stage, the voltage amplifier stage (VAS), and various parasitic and feedback-related effects.

In this work, the distortion mechanisms of a conventional three-stage Class B audio power amplifier are systematically investigated. The analyzed topology consists of a differential input stage, a voltage amplifier stage, and a push-pull emitter-follower output stage. Seven principal sources of distortion are identified and localized, including input stage nonlinearity, VAS distortion, crossover and large-signal effects in the output stage, nonlinear loading of the VAS, power-supply decoupling capacitor influence, parasitic inductive coupling, and inaccuracies in the feedback signal take-off point.

Furthermore, the frequency dependence of THD is examined under stable operating conditions across the audio band. Particular attention is given to the increase in distortion at mid- and high-frequency ranges, which is primarily associated with the combined influence of output stage nonlinearities, input stage imbalance, and feedback-related parasitic phenomena. The analysis aims to clarify the strongly coupled nature of distortion mechanisms in Class B amplifiers and to provide design-oriented insight for improving linearity and reducing THD in practical high-fidelity audio amplifier implementations.

Audio power amplifiers (APAs) are critical for high-fidelity sound reproduction, where linearity and low total harmonic distortion (THD) are essential for maintaining signal integrity. Among various designs, two-stage, three-stage, and four-stage architectures are most widely used due to their balance of performance and complexity. Despite their prevalence, achieving low THD in Class B output stages remains a significant challenge, largely due to inherent nonlinearities and crossover effects.

This study focuses on identifying and analyzing the primary sources of distortion in three-stage Class B APAs. By systematically evaluating each source and its frequency-dependent behavior, the work provides insights into design strategies for improving linearity and minimizing THD.

LITERATURE REVIEW

Audio power amplifier (APA) design has been extensively studied over the past decades, with particular focus on achieving high linearity, low total harmonic distortion (THD), and efficient power delivery. Classical works [1-3] demonstrate that two-stage, three-stage, and four-stage transistor amplifier topologies dominate practical applications due to their balance of gain, stability, and modularity. The three-stage configuration, in particular, has been widely adopted in both commercial and high-fidelity audio systems, providing effective decoupling between stages and minimizing mutual interference.

Several studies have analyzed sources of distortion in Class B amplifiers. Early investigations [4,5] highlighted the role of crossover distortion in push-pull output stages, identifying it as a major contributor to THD at low and mid frequencies. Subsequent research [6,7] focused on nonlinearity in the differential input stage, showing that input-stage imbalance significantly amplifies second- and third-order harmonics at high frequencies.

Recent advancements in feedback design and local compensation techniques [8-10] have demonstrated that careful selection of feedback sampling points, decoupling capacitors, and impedance matching can reduce high-frequency THD. However, the complex interplay of multiple distortion sources - input stage, voltage amplifier, output stage, parasitic inductances, and feedback point - remains a key challenge, particularly for Class B operation, which introduces turn-off inertia and “step” distortion effects.

Overall, existing literature establishes the necessity of a systematic, multi-source distortion analysis to guide the design of low-THD APAs. While many studies address individual stages, few provide an integrated approach that simultaneously considers all seven primary distortion sources in a three-stage Class B architecture. This gap motivates the present study.

METHODOLOGY

The study employs a combined analytical and experimental approach to investigate distortion sources in three-stage Class B audio power amplifiers. The methodology consists of the following steps:

1. Amplifier Architecture Selection
   - The analysis focuses on a standard three-stage APA (Figure 1.1) comprising:
     - Differential input stage (current-mode output)
     - Voltage-amplifying second stage (voltage-mode output)
     - Push-pull emitter-follower output stage (voltage-mode output)
2. Distortion Source Identification

o Seven primary sources of distortion were considered: input stage nonlinearity, voltage amplifier nonlinearity, output stage nonlinearity, voltage amplifier load effects, decoupling capacitor influence, parasitic inductances, and feedback sampling errors.

o Each source was analyzed individually to determine its contribution across the audio frequency spectrum (20 Hz - 20 kHz).

3. Measurement and Simulation Setup

o Amplifier operation was assumed within the linear regime, with adequate stability margins and no parasitic oscillations.

o Frequency-dependent THD was measured and/or simulated under controlled conditions:

- Load: Low-impedance resistive load
- Input signals: Sine waves of varying frequency
- Measurement instruments: Spectrum analyzers and digital oscilloscopes to quantify harmonic content

o The effects of local feedback, decoupling capacitors, and stage gain adjustments were included to isolate contributions from individual distortion sources.

4. Data Analysis

o THD versus frequency plots were generated (Figure 1.2) to visualize the relative impact of each distortion source.

o The results were analyzed to identify dominant sources across low-, mid-, and high-frequency ranges.

o Trade-offs between linearity, gain, and design complexity were evaluated to provide practical recommendations for minimizing THD in Class B APAs.

5. Assumptions

o Preamplifier operates in Class A mode to minimize input-stage distortion

o Output stage operates in Class B mode, delivering high current to a low-impedance load

o Local feedback and layout optimization are applied to reduce parasitic and coupling effects

This methodology enables a comprehensive, stage-by-stage assessment of distortion mechanisms in Class B APAs and provides a foundation for design improvements aimed at achieving low THD and high linearity.

RESULTS AND DISCUSSION

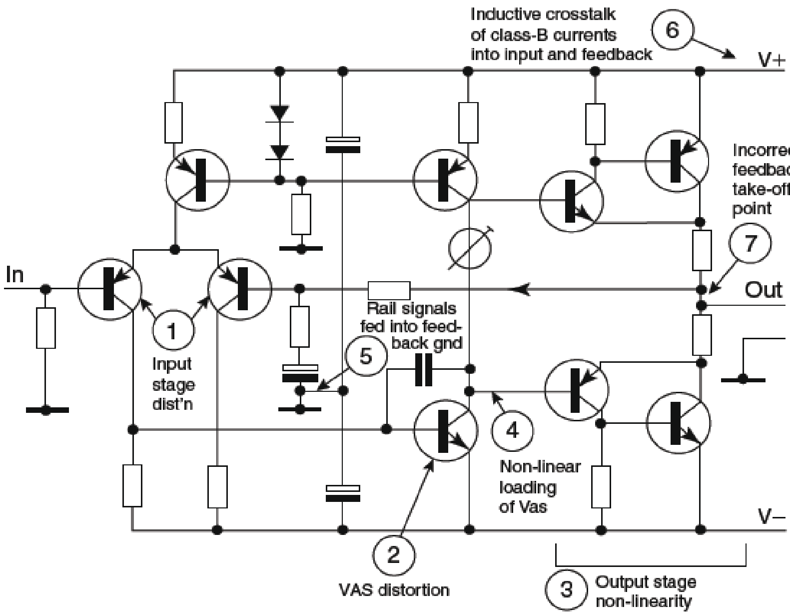

Figure 1.1. Localization of the seven primary distortion sources in a three-stage APA[1].

The study analyzes a typical three-stage APA configuration (Figure 1.1), consisting of:

1. Differential input stage - amplifies the difference between input potentials and produces a current-mode output.
2. Voltage-amplifying second stage - receives a current-mode input and outputs a voltage signal.
3. Push-pull emitter-follower output stage - transmits both input and output signals in voltage form.

The overall voltage gain of this three-stage configuration is primarily determined by the second stage; therefore, it is often referred to as the voltage amplifier. Approximately 99% of all transistor-based APAs employ this architecture due to its effective decoupling between stages, which prevents mutual interference.

Seven primary sources of distortion were identified:

1. Input stage nonlinearity
2. Voltage amplifier stage nonlinearity
3. Output stage nonlinearity (large-signal and crossover effects)
4. Nonlinearity due to voltage amplifier load
5. Decoupling capacitor-induced distortions
6. Parasitic inductances
7. Feedback signal sampling point errors

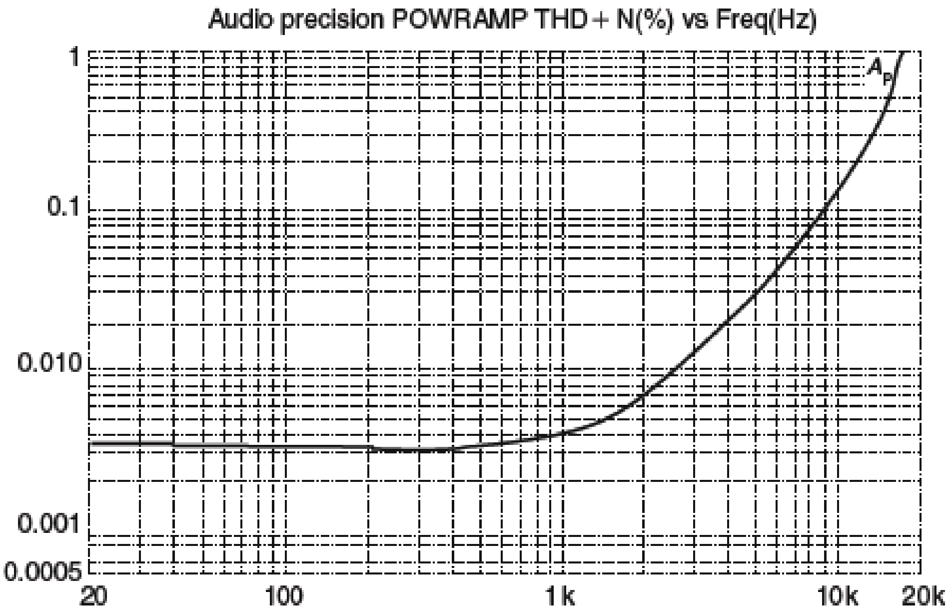

Figure 1.2. Dependence of total harmonic distortion (THD, %) on frequency (Hz) for the Class B amplifier shown in Figure 1.1[1].

For the analysis, it was assumed that the amplifier operates within the linear regime, possesses adequate stability margin, and is free from parasitic oscillations. THD was evaluated across the audio frequency range (20 Hz - 20 kHz), with emphasis on how each distortion source contributes at different frequencies.

The three-stage Class B amplifier analyzed in this study is shown in Figure 1.1. Seven primary distortion sources were identified and labeled on the schematic:

1. Input stage nonlinearity - arises from the differential input stage, producing primarily third-order harmonics in balanced configurations and second-order harmonics in unbalanced configurations.

2. Voltage amplifier stage (VAS) distortion - originates from the second stage and generally remains negligible up to the first pole frequency, increasing at 6 dB/octave thereafter.

3. Output stage nonlinearity - characteristic of Class B push-pull operation, combining large-signal and crossover distortions. These distortions increase with reduced load and are caused by turn-off delays of output transistors.

4. Nonlinear loading of voltage amplifier (VAS) - results from variations in the input impedance of the output stage, affecting linearity.

5. Decoupling capacitor effects - introduce disturbances from the power rails into the signal ground, particularly affecting low-frequency THD.

6. Parasitic inductive crosstalk - occurs due to rapid current changes in the supply circuits of the Class B output stage, inducing currents into input and feedback paths.

7. Incorrect feedback take-off point - arises when the feedback signal is taken from a point affected by output-stage supply currents, introducing additional nonlinearities.

Frequency Dependence of THD:

- Up to 500 Hz: THD ≈ 0.005%, almost constant.
- Above 500 Hz: THD increases due to contributions from sources 1-4 (assuming sources 5-7 are minimized).

Achieving a flat THD response across the audio band in Class B APAs requires trade-offs, often accepting higher low-frequency THD by increasing second-stage distortions. This complexity illustrates the difficulty of extracting high linearity from competing distortion sources, where adjusting one circuit element can affect multiple distortion mechanisms.

DISCUSSION

The analysis highlights the intrinsic challenges of achieving linearity in Class B three-stage APAs. The preamplifier generally operates in Class A, ensuring minimal distortion, while the output stage drives a low-impedance load with high current demands. Class B operation is economically and thermally favorable but introduces “step” distortions and turn-off inertia effects.

Design strategies must balance the linearity of the voltage amplifier and output stage while mitigating crossover-induced distortions. Local feedback, careful stage gain selection, and optimized feedback sampling points are essential for minimizing THD. The study confirms that addressing only one source of distortion is insufficient, as multiple sources interact across frequency bands.

CONCLUSIONS

Seven primary distortion sources in three-stage Class B APAs were systematically identified and analyzed. Key findings include:

- Low-frequency THD is negligible, but high-frequency performance is affected by input stage imbalance, output-stage nonlinearity, and feedback point selection.
- “Step” distortions and transistor turn-off delays remain critical challenges in Class B output stages.
- Design optimization, including preamplifier linearity, local feedback, and careful layout, is necessary to improve linearity and reduce THD.

These insights provide practical guidance for high-fidelity APA design and highlight areas for future research in minimizing distortions in Class B architectures.

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