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Effect of measuring response of guitar speaker cabinet using high output impedance power amplifier

***Abstract**. The article proposes utilizing a high-output impedance audio power amplifier to measure the frequency response of a guitar cabinet. The suggested solution is designed for digital modeling systems of the electric guitar sound processing path, as well as for reducing the sound pressure level of the guitar amplifier and cabinet set. Furthermore, attention is drawn to the potential application of the system in determining the impedance characteristics of the speaker set.*

***Streszczenie.** W artykule zaproponowano wykorzystanie wzmacniacza mocy akustycznej o wysokiej impedancji wyjściowej do pomiaru odpowiedzi częstotliwościowej zestawu głośnikowego do gitary częstotliwościowej. Proponowane rozwiązanie dedykowane jest systemom cyfrowego modelowania toru przetwarzania dźwięku gitary elektrycznej, jak też redukcji natężenia dźwięku gitarowego zestawu nagłośnieniowego. Zwrócono uwagę na możliwość zastosowania układu do wyznaczania charakterystyki impedancji zestawu głośnikowego. (**Zastosowanie wzmacniacza mocy o wysokiej impedancji wyjściowej do pomiaru charakterystyki częstotliwościowej gitarowego zestawu głośnikowego**)*

Keywords: vacuum tubes, digital signal processing, high output impedance power amplifier, loudspeaker
Słowa kluczowe: lampy elektronowe, cyfrowe przetwarzanie sygnałów, wzmacniacz mocy o wysokiej impedancji wyjściowej, zestaw głośnikowy

Introduction

Despite their relatively large size, weight, and low energy efficiency, tube amplifiers are still valued for their unique sound quality, comprising mostly of their nonlinear transfer function [1]. Achieving the tube sound with lower energy losses, smaller dimensions, and reduced weight is currently undergoing significant advancements. The development of Digital Signal Processing (DSP), microprocessor techniques, and Neural Networks offers compact solutions that provide similar, if not indistinguishable, sound quality to the user [2].

The increasing popularity of digital tube amplifier simulators, often combined with impulse responses of speaker cabinets, brings attention to the need for accurate modeling of the entire circuit, particularly focusing on the final elements of the signal chain: the tube amplifier output stage and speaker cabinet response. As discussed in [3], this issue can be viewed as a metrological problem, with constantly evolving models aimed at improving their accuracy.

The primary objective of this study is to investigate the impact of loading the tube amplifier output stage, considering the widely available reactive loads and attenuators. Many of these devices, particularly those in the lower price range, yield suboptimal results. This often stems from using incomplete loading methods relative to the speaker cabinet impedance characteristics, such as employing purely resistive loads, omitting parts of the impedance characteristic, or improper impedance scaling.

In [4], a comprehensive model of the tube amplifier output chain is presented, including a loudspeaker model and a simplified schematic of a push-pull tube amplifier output stage, illustrating their interrelationship. In [5], the authors present an approximated impedance equivalent of the speaker load, consisting of a parallel connection of inductance and capacitance to simulate mechanical resonance, combined with inductance and resistance in series to represent the inductive increase in impedance and the voice coil resistance of the speaker.

In [6], more precise methods for creating accurate tube amplifier loads are described, using parallel resistors to limit impedance peaks and small inductance to represent the lower DC resistance compared to the rated speaker impedance. The article proposes utilizing a high-output impedance audio power amplifier to measure the frequency response of a guitar cabinet. The proposed solution is designed for digital modelling systems of the electric guitar sound processing path, as well as for reducing the sound pressure level of the guitar amplifier and cabinet set. Furthermore, attention is drawn to the potential application of the system in determining the impedance characteristics of the speaker set.

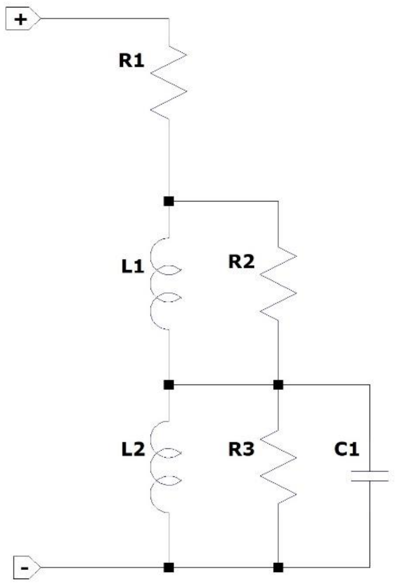

Fig. 1 Speaker cabinet impedance model used in simulations

As noted in [7] and [8], connecting the speaker to the tube amplifier output transformer effectively places the speaker impedance in series with the output tubes (multiplied by the transformer's impedance ratio). This relationship causes the tube amplifier to behave more like a current source than a voltage source. Consequently, deviations in load impedance alter the AC operating point of the circuit, influencing the output voltage.

To separate the tube amplifier from the speaker cabinet, a high-output impedance power amplifier was designed. This amplifier will be used to conduct measurements of the amplifier under various loading conditions and to drive the speaker cabinet with different output impedances.

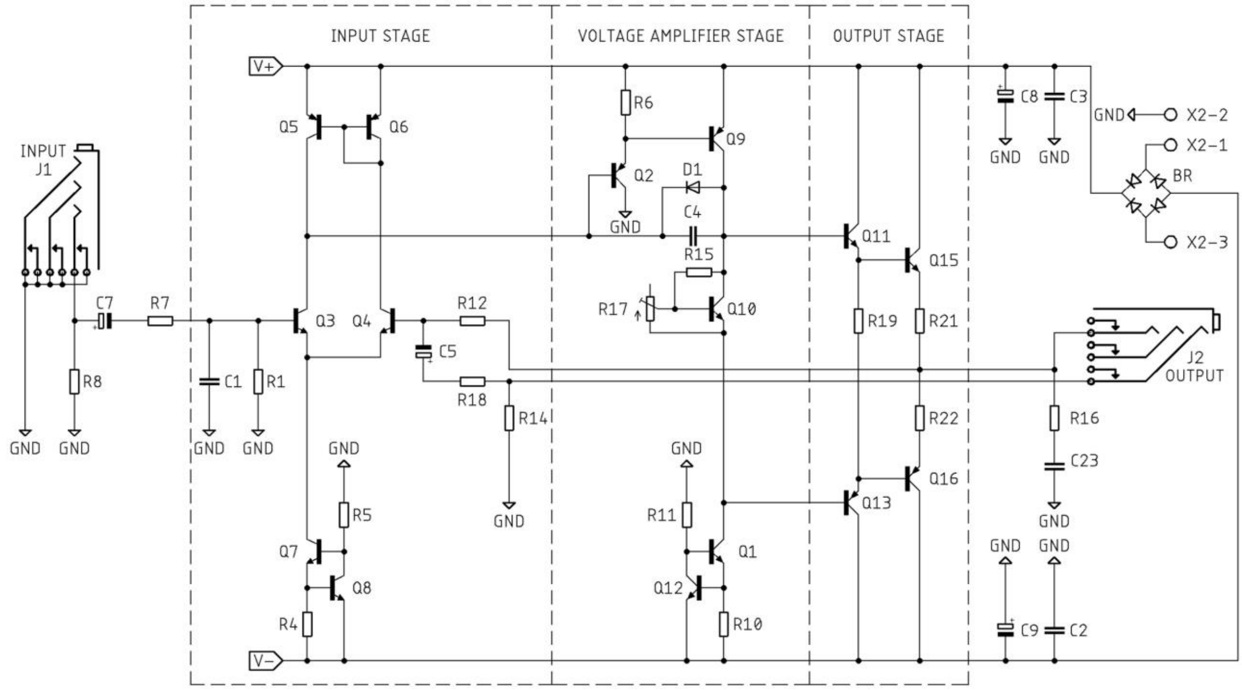

Fig. 2 Schematic of the high output impedance power amplifier

High output impedance power amplifier design

Figure 2 shows the proposed circuit schematics. J1 is the input connector, and J2 is the load connector. The circuit is powered by an external 48 V transformer with a center tap, connected via X2 to the bridge rectifier.

The power supply provides reasonably stable +/- 35 V for conducting the measurements. The overall architecture of the circuit consists of three main stages: input, voltage amplifier, and output [9]. All high-frequency and low-frequency filters were specified outside the 20 Hz – 20 kHz bandwidth.

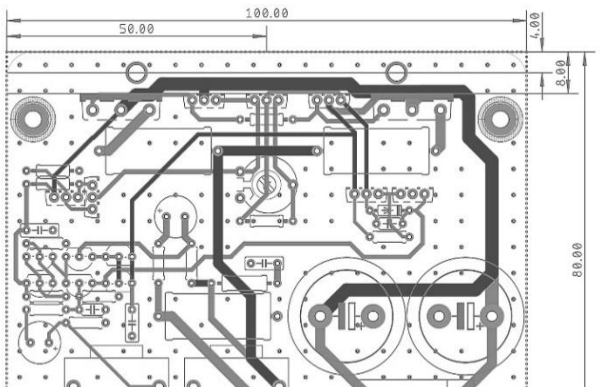

Fig. 3 PCB design of the high output impedance power amplifier

The input stage consists of a differential amplifier, made from Q3 and Q4, with current sources Q7 and Q8, and loaded with a current mirror Q5 and Q6.

The voltage amplifier stage consists of a dual transistor amplifier in a Darlington topology, made from Q2 and Q9, loaded with current sources Q1 and Q12, with a Q10 Vbe multiplier in between. D1 protects the voltage amplifier stage from failure during high output levels.

The output stage consists of two Darlington pairs: the first pair made from Q11 and Q15, and the second pair made from Q13 and Q16. The Zobel network, consisting of C23 and R16, was not populated on the printed circuit board during measurements in the high output impedance mode.

R14 controls the output impedance of the amplifier [10]. It forms a voltage divider with the load impedance while remaining inside the global negative feedback loop, providing the amplifier with adequate output current. Due to the value of this resistor being significantly smaller than if it were placed in series with the load, the load power losses are minimized. Therefore it is possible to measure the behavior of the speaker nonlinearities on high output power. By shorting it, the circuit changes its behavior to low impedance mode. Therefore, R18 should be increased in value to accommodate the change in the applied feedback level.

The printed circuit board was designed for the amplifier, as shown in Figure 3. It was designed with through-hole elements on a two-layer laminate, with a ground polygon pour and stitching with vias.

The design was thoroughly tested in simulations and showed no issues with stability and distortion, making it suitable for further use as a measurement tool.

Measurements

The measurement system consisted of the following components:

- PC with DAW and impulse response measurement software,
- Audio interface with 24-bit, 96 kHz, 8-channel ADC,
- Transformer-separated guitar splitter,
- Passive, transformer-based direct input box,
- Passive Y box,
- Commercial three-channel, EL84-based guitar amplifier,
- High output impedance power amplifier,
- Resistive load with switchable resistance,
- Commercial tube amplifier reactive load,
- Two dynamic microphones,
- Keysight 34461A multimeter,
- Agilent MSO-X 2004A oscilloscope,
- Siglent SDG1025 signal generator,
- Speaker cabinet isolation box,
- Necessary microphone stands, signal cables, and power cables.

The amplifier was chosen for its changing output impedance related to the selected mode of operation, due to the varying levels of negative feedback applied within the power amplifier section. This was confirmed by internal inspection and later in the measurements shown in Figure 5. The splitter and DI box were used to galvanically separate the circuit under test from the measurement system.

The measurements were performed in the following order, presented in Fig.4.

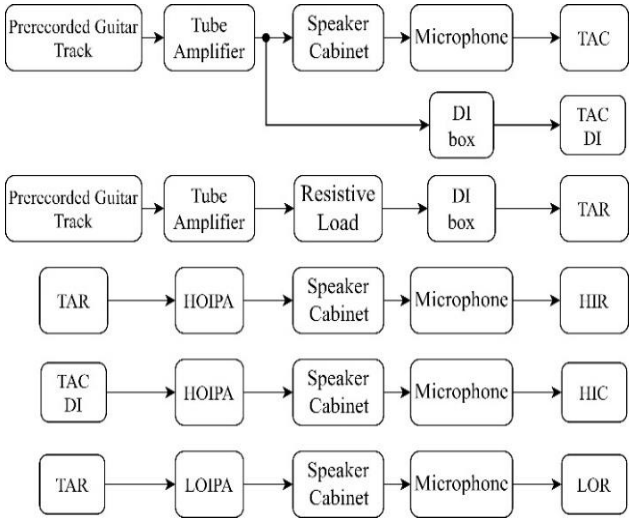

Fig. 4 Measurements order

- Measured the impedance versus frequency plot of the guitar cabinet and reactive load;
- Measured the output impedance of the guitar amplifier in both modes (closed negative feedback loop and partially open negative feedback loop);
- Set the output impedance of the power amplifier to similar levels;
- Played prerecorded guitar tracks through the tube amplifier connected to the speaker cabinet, while simultaneously recording the speaker cabinet response and the output of the amplifier (through a DI box), the cabinet recording, later referenced as **TAC** – Tube Amplifier Cabinet Load;
- Played raw DI guitar track through the tube amplifier (using the same setting as before), connected to a resistive load, and recorded the output of the tube amplifier, later referenced as **TAR** – Tube Amplifier Resistive Load;
- Played the resistive-loaded tube amplifier output through the high output impedance power amplifier (**HOIPA**) connected to speakers and recorded the speaker cabinet response, later referenced as **HIR** – High Output Impedance Resistive Load;
- Played the speaker cabinet-loaded tube amplifier through the power amplifier configured as low impedance (**LOIPA**) and recorded the speaker cabinet response, later referenced as **HIC** – High Output Impedance Cabinet Load;
- Played the resistive-loaded tube amplifier output through the power amplifier configured as low impedance and recorded the speaker cabinet response, later referenced as **LOR** – Low Output Impedance Resistive Load;
- Measured the overall response of the cabinet being driven by the high output impedance power amplifier and the aforementioned amplifier set to low output impedance mode, using Room EQ Wizard software.

The load impedance was measured by being connected to the signal generator output and the multimeter. Using the Thevenin model, which assumes the existence of an ideal signal source and ideal impedance in series with it (in this case, an ideal resistance), the voltage at the signal generator output would be proportional to the measured load impedance. The commercial reactive load impedance was measured and is presented in Fig.5.

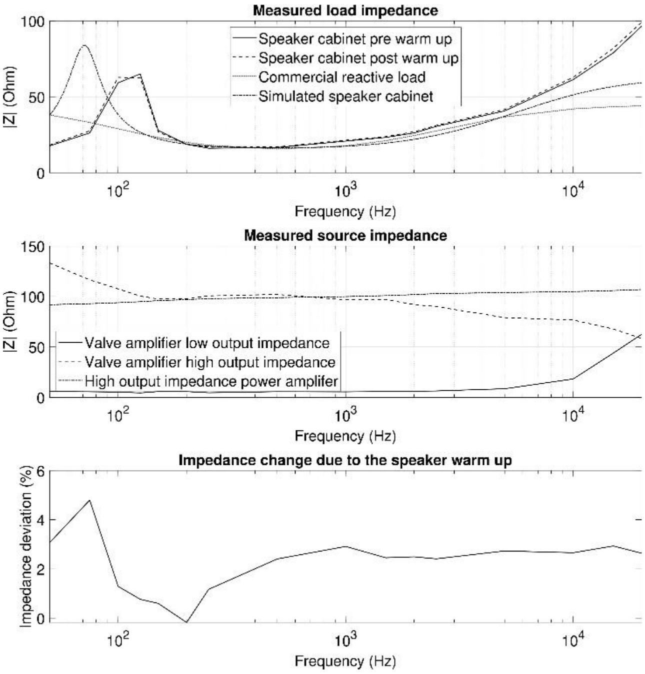

Fig. 5 Measured impedance plots

The tube amplifier output impedance was measured by loading the output with a resistive load R1, measuring the output voltage at predefined frequency points, changing the load resistance to R2, having larger value than R1, and repeating the measurements. Using the Thevenin model and equation (1), the output impedance was calculated and presented in Fig.5. The output impedance of the high output impedance power amplifier was then set to 100 Ω and confirmed by measurements.

$$Z_{OUT} = \frac{R1 \cdot R2\left(U_{R2} - U_{R1}\right)}{R2 \cdot U_{R1} - R1 \cdot U_{R2}} \quad (1)$$

Between each recording, the speaker cabinet was given a 30-minute cool-down period to minimize the possible side effects of warm-up and related speaker impedance drift. This drift was measured by applying 5 W of white noise and measuring the speaker impedance before and after, as shown in Figure 5.

The recordings were based on a selected musical piece, lasting three minutes, consisting of three guitar parts: double-tracked rhythm and one lead part. Each part was recorded in the four previously mentioned situations with two dynamic microphones placed close to the speaker cabinet grille cloth, one facing the center and one off-axis. The position of the speaker cabinet and microphones was unchanged during the measurements. The speaker cabinet was placed inside an isolation box with vibration isolation material on the floor, and walls and ceiling made from thick wool panels and sound absorption foam to minimize external sound interference. Due to the comparative nature of the work, the use of an anechoic chamber was unnecessary, and utmost care was taken to maintain constant measurement conditions.

Figure 6 presents the recorded output of the tube amplifier loaded by a speaker cabinet and a resistive load, normalized to the highest peak of each spectrum. The lower part of the figure shows the frequency-dependent amplitude difference between both situations.

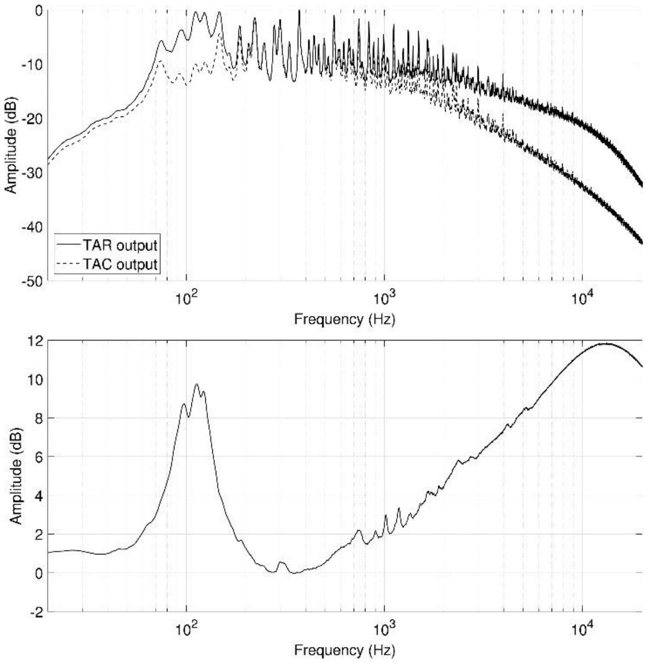

Fig. 6 Comparison of the loading effect on tube amplifier output response, top: signal frequency spectrum, bottom: amplitude difference

Figure 7 presents the response of the speaker cabinet, measured by the designed circuit in both low impedance mode and high output impedance mode, using logarithmic frequency sweep. The results were normalized to the highest peak of each spectrum. The difference in response corresponds to the measured impedance of the speaker cabinet.

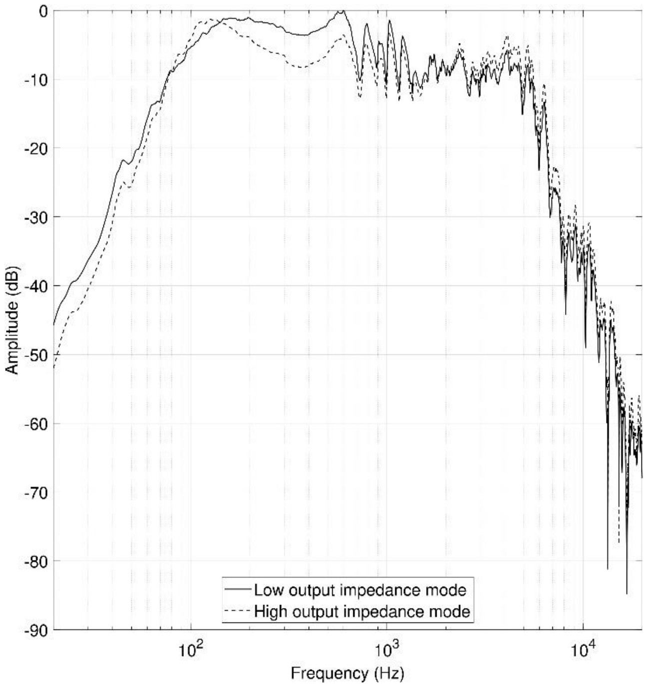

Fig. 7 Speaker cabinet response driven by designed amplifier in both modes

The recorded tracks were later processed in software to calculate the spectrum of the signal. The spectrums of the signals were normalized to the highest peak of all the signals. Figure 8 presents these spectrums, limited to four representative examples for each recording condition: tube amplifier connected to cabinet - **TAC**, response of the tube amplifier loaded by resistance and played back by high output impedance power amplifier - **HIR**, response of the tube amplifier loaded by cabinet and played back by low output impedance power amplifier - **HIC**, and response of the tube amplifier loaded by resistance and played back by low output impedance power amplifier - **LOR**.

Each of the presented responses shows differences compared to the others. TAC serves as the reference spectrum, with HIR and HIC appearing similar with their 100 Hz peak, while LOR shows the flattest response of all.

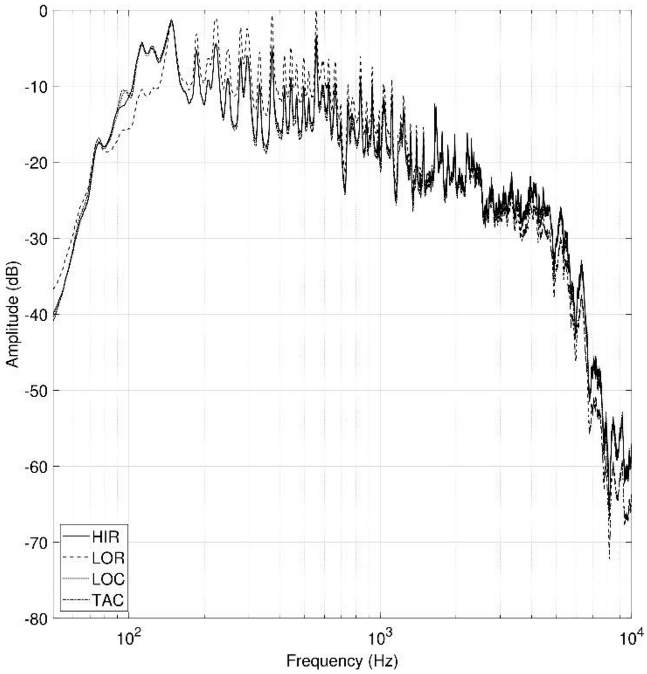

Fig. 8 FFT of recorded waveforms

Analysis

For further analysis, the bandwidth was reduced to 50 Hz – 10 kHz to eliminate the effect of the limited frequency response of the microphones and speaker cabinet on the results. Figure 9 presents the difference between selected spectrums, defined as the ratio between the selected them. It was calculated as division between magnitudes of normalized frequency responses, presented in dB scale.

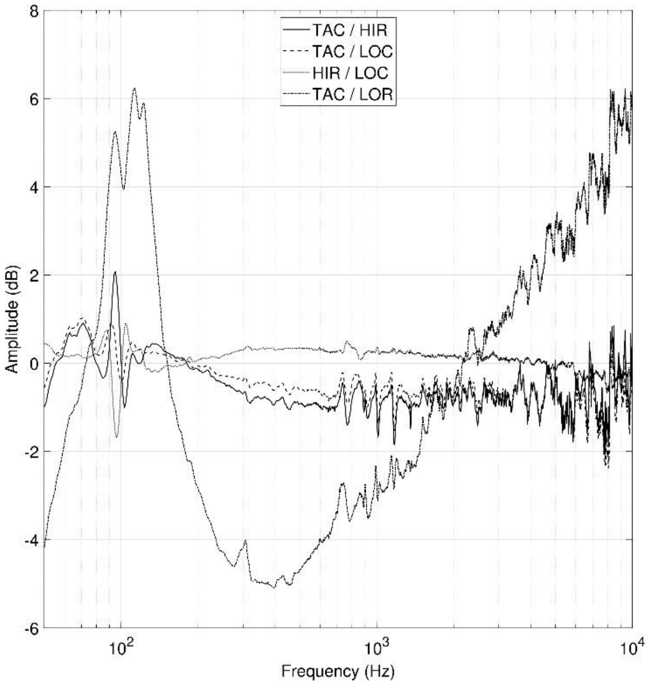

Fig. 9 Differences in recorded waveforms

Figure 9 presents a combined plot of the spectrums. The TAC/HIR and TAC/HIC differences show a small level of change in the output response of the entire circuit relative to the TAC reference. The HIR/HIC comparison presents almost no perceived change between them. The TAC/LOR comparison shows a large amplitude difference, -4 to +6 dB, reflecting the shape of the measured speaker impedance curve.

Table 1 presents the calculated mean value and standard deviation of the signal differences between the selected analyzed spectrums, within the previously mentioned 50 Hz – 10 kHz bandwidth, focusing on the frequency range limited by the microphones and speaker cabinet.

Table 1. Signal comparison

	Name	Mean [dB]	Standard deviation [dB]
1	TAC / HIC	0,69	0,49
2	TAC / LOC	0,77	0,47
3	HIR / LOC	**0,08**	**0,26**
4	TAC / LOR	2,15	2,86

As can be seen, the mean value and standard deviation are highest for the comparison between the tube amplifier connected to the cabinet and the response taken from the tube amplifier connected to the resistive load and played through the low output impedance power amplifier. This difference reaches over 2 dB in mean value and approaches 3 dB in standard deviation, with the highest peaks of the difference spectrum reaching up to 6 dB, closely following the load impedance curve.

The differences between loading the amplifier with a resistive load, followed by playing the recording through a high output impedance amplifier, and the speaker cabinet load combined with a low output impedance amplifier are relatively small. The mean value is under 0.1 dB, and the standard deviation between signals is under 0.3 dB, showing no substantial difference between these situations. Therefore we can conclude that those signals are coherent, from the musical tonality perspective.

Conclusion

In this article, the effect of measuring the response of a guitar speaker cabinet using a high output impedance amplifier, in contrast to using a low output impedance amplifier, has been demonstrated. The potential application of obtaining impulse responses of guitar speaker cabinets using both high and low output impedance power amplifiers is to improve the quality of tube amplifier simulations. This can be achieved by providing the option to implement the actual impedance plot of the speaker cabinet in the models used, adequately simulating its effect on tube amplifier distortion characteristics in relation to the used speaker cabinet.

The proposed circuit serves as a basis for a more advanced version, which could be expanded by incorporating a switchable part in the negative feedback loop, switching between low and high output impedance modes and adjusting the relative gain between them to provide similar output levels. By extending the proposed solution with computer interface, as proposed in [11], both responses could be measured without any issues and further expanding the measurement possibilities.

The effect of tube amplifier loading has been presented, highlighting the importance of obtaining proper impedance characteristics of the load for digital tube amplifier simulations.

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