Power Parameters and Efficiency of Class B Audio Amplifiers in Real-World Scenario

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Submitted July 3, 2016 / Accepted February 14, 2017

Abstract. *Consumer audio amplifiers are intended to operate with various loudspeaker loads, i.e. the load impedance profile of the audio amplifier is a priori unknown. We propose the power parameters analysis of the class B audio amplifiers to be carried out in the realistic worst-case (RWC) scenario of operation with the minimal value of the impedance and a RWC type of signal, instead of the nominal impedance of the loudspeaker and a sine-wave signal. Experimental validation, carried out for different types of signals and loudspeaker loads, demonstrate the advantages of the proposed RWC-based power parameters estimation. Furthermore, we provide a way of assessing the safe-operating area (SOA) boundaries, based on the output I-V loci of the amplifier and by means of an equivalent load line (ELL).*

Keywords

Audio, class B amplifier, power parameters, estimation, realistic worst-case scenario

1. Introduction

The consumer audio amplifiers are intended to operate with music and speech signals and various loudspeaker loads (incl. an individual transducer plus an enclosure), instead of sine-waves and resistive loads. Therefore, it makes sense to estimate the amplifier's parameters in real-world or close to real-world conditions. Here we focus on the power parameters estimation of the widely used class B audio amplifiers as these influence the choice of active components, heat sinks, and the overall power supply unit (PSU) design. The critical quantity for the active components selection is the instantaneous power dissipation while for the heat sink design this is the average power dissipation and for the PSU design – the instantaneous and the average current through the load [1].

Since both music and speech signals are stochastic and non-stationary, and the loudspeakers complex impedance is frequency-depended, exact analytical expressions for the average power parameters are hardly possible.

In [2] Raab presents expressions for the average power parameters, using the signal probability density function, in case of operation with music signals and resistive load. Zee [3] and Self [1] elaborated the idea, but still assuming that the amplifier load is purely resistive. In [4] Benjamin presents and discusses experimental results of operation of a class B amplifier in real-world conditions, but mathematical apparatus is not derived.

One way to address the above mentioned problem is by using a mathematical model and further statistical processing as shown in a previous related work [5]. A key condition for successful use of such a model is the availability of *prior* knowledge of the amplifier's load impedance response $\dot{Z}_{\mathrm{L}}(\omega)$. For instance, this is the case when the audio amplifier is being manufactured along with the loudspeaker(s) (e. g. subwoofer systems, radio receivers, etc.). However, in the following we consider that the load impedance profile is unknown in advance which is a common case, so this approach is inconvenient.

Here, we propose a method for analysis of the power parameters of class B audio amplifier, based on relations derived in a previous related work [6]. These relations are used for addressing the case of real-world signals and initially unknown loudspeaker loads. Since there are virtually infinity combinations of signals and loads, we suggest a realistic worst-case (RWC) scenario of amplifier operation. In addition, we propose a way for charting the safe-operating area (SOA) boundaries of the active components in the amplifier's output stage, which allows an estimation of the instantaneous power dissipation and the peak collector current to be made, in the light of SOA boundaries.

2. Proposed Method

We propose the power parameters analysis to be carried out for the RWC scenario of operation with the minimal value $Z_{\mathrm{Lmin}} = \min(Z_{\mathrm{Lnom}})$ of the loudspeaker impedance, instead of the nominal impedance Z_{Lnom}, as well as with RWC type of music signals, instead of sine-wave. Typical minimal values of the loudspeaker impedance are $Z_{\mathrm{Lmin}} \in \{2.75, 5.5\}\ \Omega$ for $Z_{\mathrm{Lnom}} \in \{4, 8\}\ \Omega$. Our considerations are: the operation with sine-wave signals is not representative for the amplifier exploitation conditions, and since the sine-wave parameters are worse (as shown below) in comparison with these of music signals, the amplifier power parameters would be overestimated. Furthermore, the loudspeaker impedance modulus in a wide frequency range is below Z_{Lnom}, so the analysis should consider the worst case scenario of operation with Z_{Lmin}. Then, the average values of the power parameters of a class B audio amplifier could be calculated as for a sine-wave operation [7], using two correction coefficients ξ_{eq} and χ defined in [6]. The equivalent coefficient of the power supply voltage ξ_{eq} is defined as

$$\xi_{\mathrm{eq}} = \frac{CF_{\mathrm{sin}}}{CF_{\mathrm{rand}}} \cdot \frac{\max\left(\left|u_{\mathrm{out}}(t)\right|\right)}{U_{\mathrm{cc}}} = \frac{CF_{\mathrm{sin}}}{CF_{\mathrm{rand}}}\xi \qquad (1)$$

where CF_{sin} and CF_{rand} are the crest-factors for sine-wave and random signals , $u_{\mathrm{out}}(t)$ is the amplifier output voltage, U_{cc} is the power supply voltage, and ξ is the coefficient of the power supply use for sine-wave signals.

The coefficient of average rectified values compliance χ is given as

$$\chi = \frac{FF_{\mathrm{sin}}}{FF_{\mathrm{rand}}} \qquad (2)$$

where FF_{sin} and FF_{rand} are the signal form-factors for sine-wave signals, and for signals with random distribution, respectively. The values of CF and χ for certain signals of interest are: (i) CF = 3.01 dB, $\chi = 1$ for a sine-wave signal; (ii) CF = 10÷20 dB, $\chi = 0.5\sqrt{\pi}$ (assuming Gaussian amplitude distribution) for music signals [1–3], and (iii) CF = 15÷25 dB, $\chi = 0.25\pi$ (assuming Laplace amplitude distribution) for speech signals [3], [8]. Ultimately we consider music with CF = 6 dB as the RWC type of signal, since there is no evidence smaller CF to be found in practice.

The definitions for the average power parameters and efficiency of a class B audio amplifier for resistive loads and any type of signals [6] are as follows:

$$P_{\mathrm{DC}} = \frac{2U_{\mathrm{cc}}^2}{\pi R_{\mathrm{L}}}\xi_{\mathrm{eq}}\chi\,, \qquad (3)$$

$$P_{\mathrm{L}} = \frac{U_{\mathrm{cc}}^2}{2R_{\mathrm{L}}}\xi_{\mathrm{eq}}^2\,, \qquad (4)$$

$$P_{\mathrm{D}} = P_{\mathrm{DC}} - P_{\mathrm{L}} = \frac{U_{\mathrm{cc}}^2}{R_{\mathrm{L}}}\left(\frac{2\xi_{\mathrm{eq}}\chi}{\pi} - \frac{\xi_{\mathrm{eq}}^2}{2}\right), \qquad (5)$$

$$\eta = \frac{P_L}{P_{\mathrm{DC}}} = \frac{\pi}{4}\frac{\xi_{\mathrm{eq}}}{\chi}\,. \qquad (6)$$

In (3)-(6), P_{DC} is the power drawn from the PSU, P_{L} is the power delivered to the load, P_{D} accounts for the losses in the amplifier, and η is the amplifier efficiency.

In order to assess the maximum value of the instantaneous collector current $i_{\mathrm{C}}(t)$ and the SOA boundaries we use assessment based on the output I-V loci of the amplifier (collector current i_{C} vs. collector-emitter voltage u_{CE} plots) and an equivalent load line (ELL) [1]. However, here we consider the RWC-signal and not sine-wave signals, and Z_{Lmin} instead of Z_{Lnom}. Therefore, we propose the ELL to be drawn on the amplifier output I-V locus by defining two points with Cartesian coordinates A $(0, I_{\mathrm{Cmax}} = U_{\mathrm{cc}}/\,Z_{\mathrm{Lmin}})$, B $(U_{\mathrm{CEmax}} = 2U_{\mathrm{cc}}, 0)$.

One should be aware that the RWC output I-V loci are not below the ELL by default and the ELL could be exceeded, although this rather rarely happens [1, 4].

3. Analytical, Numerical and Measurement Results

Equations (3)-(6) were evaluated for two representative cases: (i) the classic design with a sine-wave signal ($R_{\mathrm{L}} = Z_{\mathrm{Lnom}} = 8\ \Omega$, CF = 3.01 dB, $\chi = 1$) and (ii) the RWC-based design ($R_{\mathrm{L}} = Z_{\mathrm{Lmin}} = 5.5\ \Omega$, CF = 6 dB, $\chi = 0.5\sqrt{\pi}$). In both cases U_{cc} = 12 V and $\xi = 0.85$.

We carried out numerical experiments using the SiPoLo-model [5, 9] (cf. Fig. 1) in order to assess the average power parameters, the efficiency and the output I-V locus of a given class B audio amplifier for different types of signals and loudspeaker loads.

Two test signals are used: (i) a test signal defined by CEA-426-B (formerly EIA-426-B) standard [10] (which is considered to be a good approximation of the music signals [3, 11]) with duration 30 min and CF = 6 dB, and (ii) music (hours of different genres from commercial CDs). The amplifier loads were various types of loudspeakers, incl. subwoofers, mid-ranges and tweeters with impedance response modeling as is shown in the Appendix.

The numerical experiments were repeated as real-word measurements under the same conditions using audio power amplifier based on IC LM3886 [12] in a follower configuration. The output voltage and the current through the load were measured using data acquisition system NI USB-6211 and the amplifier parameters of interest were evaluated.

Some of the results of the analytical, numerical and real-world estimation procedures are shown in Tab. 1, Fig. 1 and Fig. 2. We present the results and the output I-V loci for the CEA-426-B test signal and for 90 min music signal from the DVD "Stars of the 90's Volume 01" (DVD

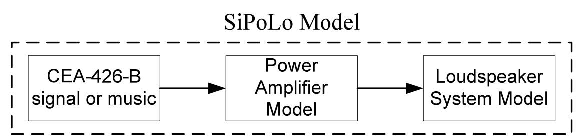

Fig. 1. Block diagram of the SiPoLo-model used for numerical estimation of the amplifier power parameters for different types of signals and loads.

Test conditions (TC)		P_{DC} [W]	P_D [W]	P_L [W]	η [%]
1.	Classic estimation	9.74	3.24	6.50	66.8
2.	RWC-based estimation	8.90	4.15	4.75	53.4
3.	18W/8424G00 in 4th order bandpass double chamber box, CEA-426-B signal (simulation)	5.98	3.72	2.26	37.7
4.	18W/8424G00 in 4th order bandpass double chamber box, music (simulation)	2.22	1.83	0.38	17.3
5.	Unknown single loudspeaker system, CEA-426-B signal (measurement)	5.73	3.36	2.37	41.3
6.	Unknown single loudspeaker system, music (measurement)	3.13	2.34	0.79	25.2

Tab. 1. Results from analytical, numerical and real-world estimations of power parameters of a class B audio amplifier.

10501200501) played on loudspeaker 18W/8424G00 [13] mounted in 4th order bandpass double chamber box and a single loudspeaker system with unknown loudspeaker and enclosure parameters.

4. Discussion

The analytical study and the experimental results led us to the following:

1. The power parameters values of the amplifier operating with CEA-426-B test signal are always greater than these of music signals (cf. Tab. 1 TC 3-4 and TC 5-6). This holds true for subwoofers, mid-ranges and tweeters, regardless of the different mechanical resonant frequencies. Hence, the CEA-426-B test signal could be successfully used as a RWC-signal.

2. The power parameters in all tests are well below the values calculated via RWC-based estimation, especially for music signals (cf. Tab. 1 TC 2-4 and TC 2-6). Therefore, for the class B audio amplifiers the RWC-approach could be considered as a good estimator of the power parameters in a real-world scenario.

3. The values of P_{DC} and P_L obtained via RWC-based estimation are always lower than these obtained by the classic approach (cf. Tab. 1 TC 1-2). This allows lowering the design requirements for both the amplifier PSU and the loudspeaker.

4. The actual value of P_D could be greater than the one obtained through the classic estimation, which has to be taken into account in the design of the amplifier's heat sink(s) (cf. Tab. 1 TC 1-3 and TC 1-5).

Consequently, the presented RWC-based estimation of the power parameters and efficiency of the class B audio amplifiers is more relevant than the classic approach, because it approximates more accurately the real-world parameters of interest.

Furthermore, we can make the following conclusions based on observations of the amplifier loci:

1. There is no evidence that the maximum value of the instantaneous collector current $i_C(t)$ would exceed the value I_{Cmax} calculated by (7) (cf. Fig. 1 and Fig. 2), which facilitates the active components selection and the PSU design.

2. Virtually all the I-V loci of the amplifier are below the ELL (cf. Fig. 1 and Fig. 2) with minor exceptions, generally when operating with the CEA-426-B signal.

Hence, the ELL could be considered as a good estimator for SOA limitations of the amplifier in real-world conditions. Our conclusions are in good agreement with the empirical results shown in [4], performed with numerous loudspeakers and hundred hours of music.

There is possibility to decrease the dissipated power P_D and to increase the efficiency η of the class B power amplifiers via loudspeaker system's impedance compensation using an appropriate Zobel network [14, 15]. Thus the impedance profile of the amplifier's load will have a (close to) resistive nature (in the frequency band of operation) and this is proved to be the optimum case of operation in the light of amplifier efficiency [16]. Also, this approach is

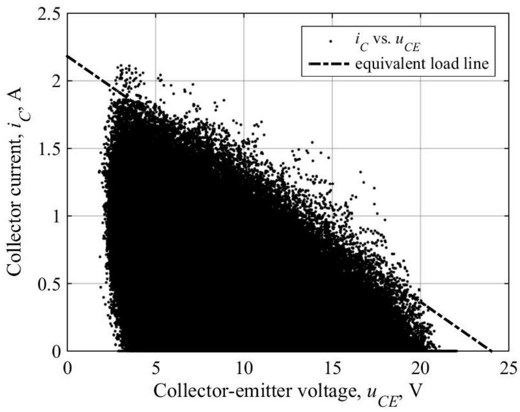

Fig. 2. Output I-V locus of the analyzed amplifier playing CEA-426-B test signal on 18W/8424G00 mounted in 4th order bandpass double chamber box.

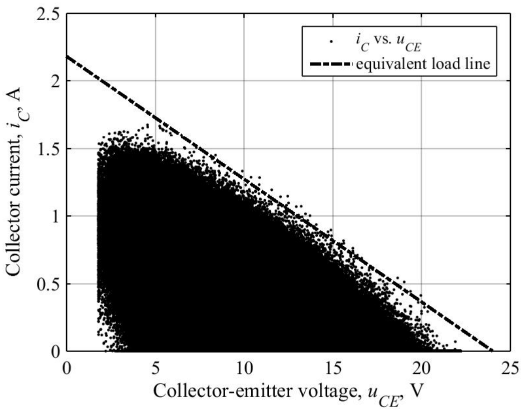

Fig. 3. Output I-V locus of the analyzed amplifier playing music on 18W/8424G00 mounted in 4th order bandpass double chamber box.

extremely effective in reducing of the peak instantaneous power dissipation of the amplifier [4]. One must be aware that this is possible only if there is a *prior* knowledge of the amplifier's load impedance response $\dot{Z}_L(\omega)$.

5. Conclusion

A new approach for estimation of the power parameters of the class B amplifiers is proposed, based on RWC scenario of operation with the minimal value of the loudspeaker impedance and a RWC type of signal, instead of the nominal impedance of the loudspeaker and a sine-wave signal, respectively. It is shown that the considered RWC-estimation approximates more accurately the real-world power parameters of the audio amplifier. This is of particular importance when the load impedance profile of the audio amplifier is *a priori* unknown, which is the common case in the practice. Also, assessing of the SOA boundaries based on the output I-V loci of the amplifier and by means of ELL is presented.

The analytical study and the experimental results show that the values of P_{DC} and P_L obtained via the RWC-estimation are always lower than these obtained via the classic approach, but P_D could be greater. Lowering the design requirements to the PSU of the amplifier and the loudspeaker allows cheaper electronic components, heat sinks, and loudspeakers to be used. This offers opportunities for reducing the prime cost of the product. The awareness about the higher value of P_D in real-world conditions allows an appropriate choice of the active components and heat sink(s) to be made and hence improves the amplifier robustness.

Further study should be carried to derive practical design of class B amplifiers, based on the RWC-estimation of the power parameters presented here, including loudspeaker system's impedance compensation.

Appendix

In this Appendix, we briefly illustrate the loudspeaker system impedance response modeling technique used in the SiPoLo-model.

The simplified electrical equivalent circuit of a 4th order bandpass double chamber loudspeaker system is shown in Fig. A1 [17].

The electrical impedance of the system includes the sum of the voice coil electrical impedance, the impedance introduced by the mechanical system and one by the acoustic volume [17]

$$\dot{Z}_L(j\omega) = R_e + j\omega L_e + \frac{(B.l)^2}{R_{ms} + \frac{1}{j\omega C_{ms}} + \frac{S_d^2}{j\omega C_{ab1}} + j\omega M_{ms} + \frac{S_d^2}{j\omega C_{ab2} + \frac{1}{R_{aL}} + \frac{1}{j\omega M_{ap2}}}}. \quad (A1)$$

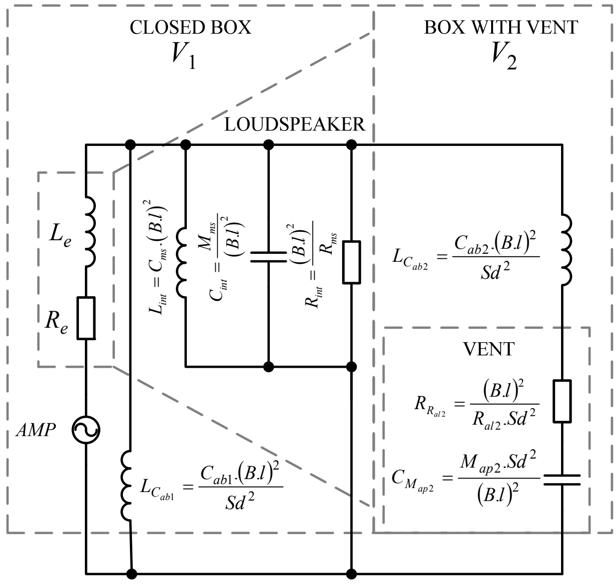

Fig. A1. Simplified electrical equivalent circuit of the 4th order bandpass double chamber loudspeaker system.

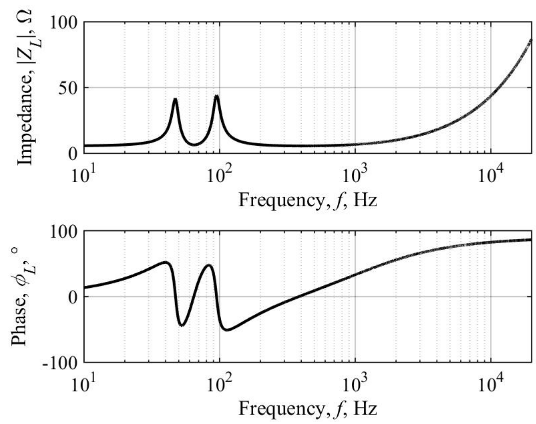

Fig. A2. Impedance response (magnitude and phase) of the 18W/8424G00 loudspeaker mounted in 4th order bandpass double chamber box.

The amplitude and phase of the impedance response of the 18W/8424G00 loudspeaker mounted in 4th order bandpass double chamber box used in the experiments, is shown in Fig. A2. Additional information on loudspeaker system impedance modeling could be found in [18–21].

Acknowledgments

The authors would like to express their deep gratitude to Assoc. Prof. Ph.D. Todor Ganchev for the appropriate recommendations and advices.

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