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Efficiency Investigation of Switch-Mode Power Audio Amplifiers Driving Low Impedance Transducers

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ABSTRACT

The typical nominal resistance span of an electro dynamic transducer is 4 Ω to 8 Ω . This work examines the possibility of driving a transducer with a much lower impedance to enable the amplifier and loudspeaker to be directly driven by a low voltage source such as a battery. A method for estimating the amplifier rail voltage requirement as a function of the voice coil nominal resistance is presented. The method is based on a crest factor analysis of music signals and estimation of the electrical power requirement from a specific target of the sound pressure level. Experimental measurements confirms a huge performance leap in terms of efficiency compared to a conventional battery driven sound system. Future optimization of low voltage, high current amplifiers for low impedance loudspeaker drivers are discussed.

1. INTRODUCTION

A system designed for high quality audio reproduction involves many different blocks. These often include power supply, Digital Signal Processing (DSP), pre-amplifier, amplifier, cross-over network, loudspeaker enclosure and transducer. However all these blocks can be boiled down to three essential blocks which are:

- Power supply
- Amplifier
- Transducer

Modern power supplies and amplifiers are widely utilizing switch-mode power technology which is described in [1]. This is due to the high efficiency this technology offers, which theoretically can reach 100%. In practice the theoretical efficiency cannot be reached but it is possible to reach efficiencies above 90% for audio applications [2] and [3]. Moreover the switch-mode power audio amplifiers delivers excellent audio performance with Total Harmonic Distortion (THD) beneath 0.005% [4]. The transducer of the sound system, also referred to as the loudspeaker driver, is normally mounted in a care-

fully designed enclosure. Loudspeaker drivers and their enclosures are well described in literature [5], [6], [7]. The impedance of the driver consist of an acoustical-, a mechanical and an electrical-part and is carefully described in [8] and [9]. The nominal resistance of the driver is characterized by the voice coil resistance. This resistance is also know as the DC resistance, corresponding to the resistance at 0 Hz. For decades it has been widely accepted to aim for voice coil DC resistances between 4 Ω and 8 Ω . According to Joules and Ohms laws a reduction of the load impedance leads to a decreased amplifier voltage rail requirement and an increased current requirement for a given output power:

$$U = \sqrt{P \cdot R}, \quad I = \sqrt{\frac{P}{R}} \quad (1)$$

In traditional sound systems where relatively long cables connect the amplifier to a number of passive loudspeakers the high current requirement would result in high conduction losses or very thick cables which are clear disadvantages. In these systems a load in the range of 4 Ω to 8 Ω is still preferable. In integrated sound systems or active loudspeakers where the amplifier is located in close proximity to the transducer a low impedance load could be advantageous. Modern switch-mode power audio amplifiers can easily be designed to deliver power to lower load impedances. A low amplifier voltage rail requirement will enable the amplifier to be driven directly from a low voltage source such as batteries without the need of an extra power conversion utilizing a switch-mode power supply. In battery powered audio applications this will lead to reduced size, cost and weight as well as increased efficiency. The increased efficiency could either be exploited to prolong the operational time between charging or to reduce the battery size leading to additional cost, size and weight benefits. On the transducer side a lower voice coil DC resistance can be obtained using rectangular or foil windings resulting in higher fill factors which can benefit the efficiency of the transducer, as discussed and shown in [11] and [12].

This paper will focus on the consequences for the power electronics, e.i power supply and audio amplifier, when utilizing low impedance loudspeaker drivers.

2. VOLTAGE RAIL ANALYSIS

Switch-mode power audio amplifiers normally utilizes a Buck topology [1]. This topology can be realized either in a half- or full-bridge configuration. The half bridge requires a dual voltage supply while the full bridge only requires a single supply. However the component count in the full bridge is twice the component count in the half bridge. For battery driven systems the full bridge Buck, shown in fig. 1, is the conventional used topology. The Buck

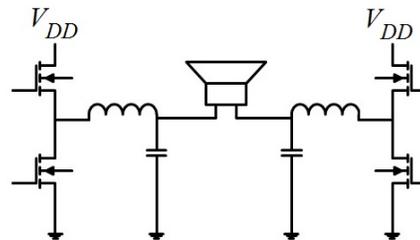


Fig. 1: Full bridge buck topology.

topology has an ideally linear steady state transfer function, enabling low THD, which makes it suitable for audio applications. The steady state transfer function for the full bridge Buck is shown in eq. 2.

$$V_o = (2D - 1) V_{DD} \quad (2)$$

Where D is the duty cycle, V_{DD} is the supply rail voltage and V_o is the output voltage. It is seen that when the duty cycle is either 0% or 100% the maximum output voltage is obtained $|V_{o,max}| = |V_{DD}|$. The peak output power is simply:

$$P_{pk} = \frac{|V_{DD}|^2}{R_L} \quad (3)$$

Where R_L is the load resistance which equivalent the transducer impedance. For DC-DC operation the maximum output power can be found using eq. 3. However when operated with dynamic signals one have to take the crest factor (CF) of the signal into account. The crest factor is the ratio between the peak and the rms value of a signal and is normally given in decibels.

$$CF = 20 \log \left(\frac{V_{pk}}{V_{rms}} \right) = 10 \log \left(\frac{P_{pk}}{P_{rms}} \right) \quad (4)$$

For test purposes audio signals are normally estimated with sine waves, which have a crest factor of:

$$CF_{sine} = 20 \log(\sqrt{2}) = 3 \text{ dB} \quad (5)$$

While the peak power remains the same for signals with different crest factor, the maximum continuous output power, e.i the RMS output power, is strongly affected:

$$P_{RMS} = \frac{P_{pk}}{\exp\left(\frac{CF \cdot \ln(10)}{10}\right)} \quad (6)$$

The voltage rail requirement should satisfy eq. 3.

$$V_{DD} = \sqrt{R_L P_{pk}} \quad (7)$$

In order to determine the required rail voltage the crest factor and the maximum RMS output power must be known. These quantities will be examined in the next chapters.

3. CREST FACTOR ANALYSIS

As mentioned sine waves are normally used for test purposes of audio amplifiers. However real music signals are much more dynamic than sine waves. This is described in [13] and [14], where it is also shown that the crest factor depends a lot on the genre of music. In [15] the historic evolution of the crest factor is described. Here it is stated that the crest factor has been decreasing since the nineties due intensive compressor use in the mastering process of an audio recording.

The difference between audio signals and sine waves can be visualized when investigating the actual signal amplitude distribution of audio tracks and sine waves. Fig. 2 shows the signal amplitude distribution of more than 400 different audio tracks and compares it to that of a sine wave. From the figure it is seen that even though the amplitude peaks are the same, the amplitude of the audio tracks is concentrated around zero while the sine signal amplitude is distributed more evenly and actually increases in the outer regions. From fig. 2 it can be easily realized that the RMS value of the audio tracks are significantly smaller than that of the sine wave. Moreover this means that the resulting crest factor of the audio tracks are significantly larger than that of the sine wave. The amplitude bins used in the analysis

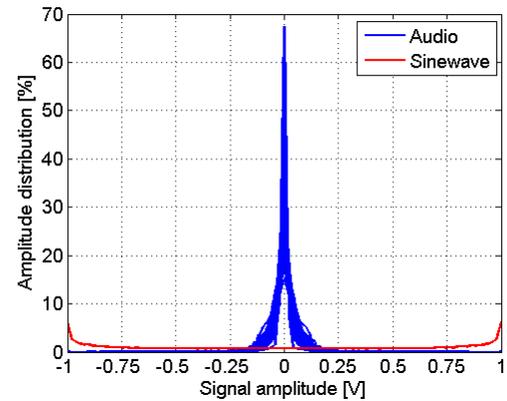


Fig. 2: Amplitude distribution of music compared to a sine wave

were 0.1 V which explains why the amplitude distribution does not reach 0 at high signal amplitude for the sine wave. To get a good estimation of the average crest factor of audio tracks, the crest factors of +400 audio tracks have been analysed. Not only have this analysis been performed on the original audio signals but also on a low pass-, a band pass- and a high pass-filtered version of the original signal. By doing so one obtain an example of crest factors of actual audio signals delivered to a subwoofer, a woofer and a tweeter, as shown in fig. 3, displayed as box plots. From the figure it is evident

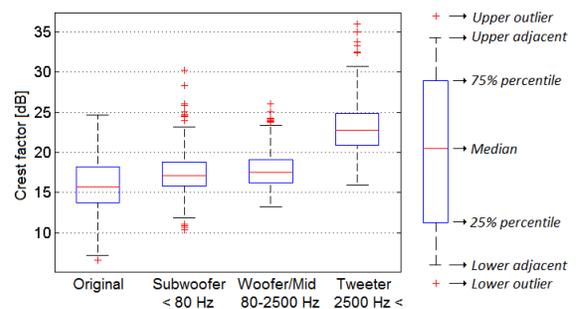


Fig. 3: Calculated crest factor of +400 original and filtered audio signal

that the crest factor span is huge. For the original signal we find crest factors ranging from 5 dB up to 25 dB. However when focussing only on the 25%

Crest factor	Original	Subwoofer	Woofers/Mid	Tweeter
High	18 dB	19 dB	19 dB	25 dB
Medium	16 dB	17 dB	17 dB	23 dB
Low	14 dB	16 dB	16 dB	21 dB

Table 1: Most common crest factor span

percentile to the 75% percentile, e.i the tracks with the most common crest factor value, it is seen that the crest factor ranges approximately from 14 dB to 18 dB with the median value of 16 dB. This result is summarized in table 1.

From fig. 3 it is observed that the crest factor for the subwoofer- and woofer-filtered signals are quite similar to that of the original. The tweeter-filtered signals has, on the other hand, a much higher crest factor. Equal rail voltages may however be utilized for all loudspeaker driver types due to the relative lower power requirement of tweeters [13].

Due to loudness normalization, tracks with different crest factors will sound equally loud when played back over an audio system. However the music with high crest factor will demand power peaks which are greater than that of the music with low crest factor. Higher power peaks equals higher output voltage peaks and in order to deliver these peaks without clipping one must ensure that voltage rail of the amplifier is of sufficient size as shown in fig. 4.

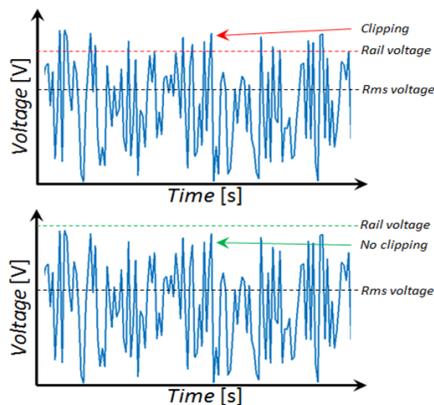


Fig. 4: Music signal gets distorted when rail voltages are insufficient.

4. EXAMPLE OF VOLTAGE RAIL REQUIREMENT

Consider the sound system shown in fig. 5 playing into a half sphere environment. r is the distance from the transducer to the listener in meters, P_{out} is the electrical output power of the amplifier and P_A is the acoustical output power. Assuming that the

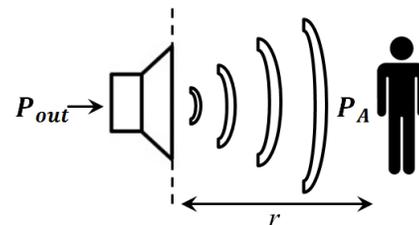


Fig. 5: Sound system with listener at a distance of r away from transducer.

desired maximum continuous sound pressure level (SPL) at the listener's position is 93 dB, which is a rather loud sound pressure level, we can calculate the maximum continuous electrical output power using:

$$P_{RMS} = 10^{\frac{SPL}{10}} P_o A \eta_0^{-1} \quad (8)$$

Where $P_o = 10^{-12} \text{ W/m}^2$ is the reference acoustic sound power, $A = 2\pi r^2$ is the area of the sound surface at a given distance from the driver and η_0 is the efficiency of the driver. With the listener placed 1 meter from the transducer, which is a standard loudspeaker driver with an efficiency of 0.61%, corresponding to a loudspeaker sensitivity of 90 dB (1W@1m), we get:

$$\begin{aligned} P_{RMS} &= 10^{\left(\frac{93dB}{10}\right)} 10^{-12} 2\pi 1^2 0.0061^{-1} \\ &= 2 \text{ W} \end{aligned} \quad (9)$$

This is the maximum RMS output power which this system should provide in order to generate the de-

sired sound pressure level. The peak power requirement is 126 W based on equation (4) and a crest factor of 18 dB. This power requirement is most likely overestimated, due to the fact that normal listening conditions are not in perfectly half sphere environment, but in a room. However we can use eq. 7 and the crest factor span from table 1, to obtain an estimate of the requirements to the voltage rail as a function of the DC resistance as seen in fig. 6. This graph simplify the selection of the voice coil DC resistance as a function of a given battery supply.

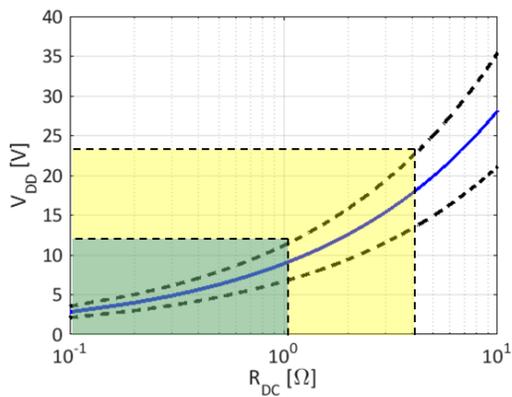


Fig. 6: V_{DD} vs. R_{DC} for an output power of $P_{RMS} = 2$ W including crest factor span of the unfiltered audio tracks. The solid line is for $CF = 16$ dB. For low load resistances, up to 1Ω , the desired output power can be obtained directly from a 12 V battery supply (the green box). For a typical 4Ω load a voltage rail of 24 V is required (the yellow box).

5. EXPERIMENTAL RESULTS

Figure 7 shows the hardware used during the experimental work (left: power supply, right: amplifier). The power supply is a 150 W boost converter (based on UC3843 from Texas Instruments) that can handle 10 - 32 V_{DC} on the input and 12 - 35 V_{DC} on the output. The dimensions are 6.5 cm x 4.8 cm x 2.5 cm. The amplifier is a 2 x 50 W class-D amplifier (based on the TPA3116D2 from Texas Instruments) with a working rail voltage of 6.5 V_{DC} to 26 V_{DC} . The dimensions are 8 cm x 7 cm x 2.5 cm.



Fig. 7: Power supply (left) and amplifier (right)

5.1. Amplifier Efficiency

To study the consequences of driving a low impedance load with a commercial available class-D amplifier the amplifier efficiency was measured driving a standard 4Ω load resistance with a rail voltage of 24 V and a 1Ω load resistance with a rail voltage of 12 V - see figure 8. It is observed that the amplifier efficiency driving a 1Ω resistive load is greatly improved below 2 W, which was the previously estimated maximum continuous power level. This is due to lower switching losses, [10]. In addition to this the continuous output power level will be below 2 W when the user listens to background music. It is expected that the efficiency of a low voltage and high current amplifier can be further improved since the amplifier under test was not optimized for driving a low impedance. This issue will be addressed in a later discussion.

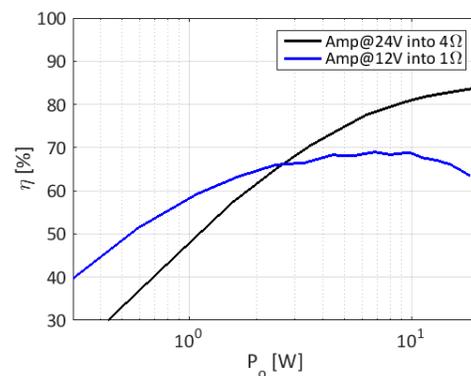


Fig. 8: Efficiency measurements

5.2. Battery Powered Audio Systems

As mentioned before one of the major advantages of a low impedance loudspeaker would be the ability to drive the amplifier and the loudspeaker directly from a low voltage source without the need for an additional power conversion unit such as a switch mode power supply. Figure 9 illustrate the test setup of a conventional battery powered sound system consisting of a battery, a power supply, an amplifier and a 4 Ohm load and the proposed direct drive sound system with a low impedance load simplified by a 1 Ω resistance. The measured efficiency of the two sys-

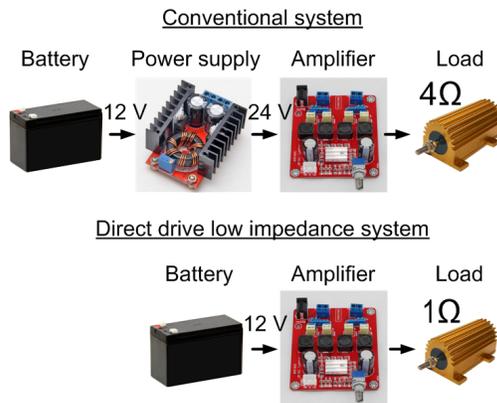


Fig. 9: Measurement setup

tems are shown in figure 10. Even though the power supply is fairly efficient (see figure 11) the efficiency of the direct drive and low impedance sound system obtain a significant higher efficiency, especially for light loads. As the power increases conduction losses begins to dominate and we see a decrement of the efficiency of the direct drive setup. This is expected due to the fact that the amplifier used is not optimized for high currents. It could be argued that a higher efficiency of the conventional system could be achieved by intelligent on/off control of the power supply as a function of the signal amplitude. But besides an increased control complexity this would still demand a power supply in the system which leads to increased cost, size and weight.

6. DISCUSSION AND FUTURE WORK

The experimental result clearly show an advantage in terms of system efficiency for battery powered

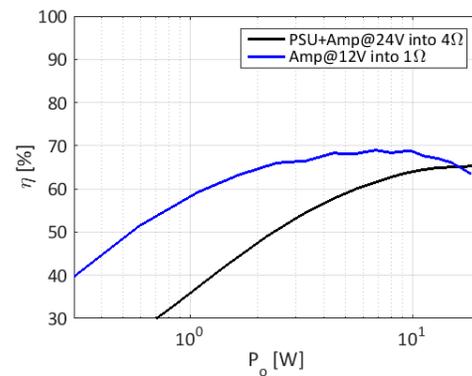


Fig. 10: Efficiency measurements of conventional vs. direct drive sound system

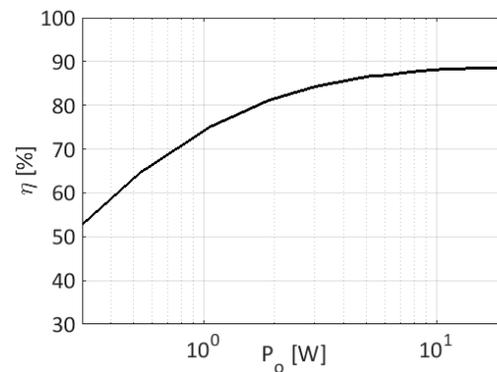


Fig. 11: Efficiency measurements of the power supply

low impedance transducers. A further efficiency increase can be obtained by improving the amplifier design. The low voltage rail requirement open up the possibility of using switching devices with a low voltage rating. Table 2 show a small selection of MOSFET's with extreme characteristics chosen for either low drain-source resistance or low gate charge and input capacitance. It is noted that a low drain-source voltage MOSFET offer a lower R_{DS} , Q_G and C_{iss} . Despite the voltage rating, the right balance between these parameters is important to optimize the amplifier efficiency. Amplifiers for driving low impedance transducers where the output current is high would benefit from a low drain source resistance

Part number	Package	V_{DSS}	R_{DS}	Q_G	C_{iss}
IPT004N03LATMA1	8-PowerSFN	30 V	0.4 m Ω	163 nC	24 nF
PMZ350XN,315	SOT-883	30 V	420 m Ω	0.65 nC	37 pF
IPT015N10N5ATMA1	8-PowerSFN	100 V	1.5 m Ω	211 nC	16 nF
FDMA86108LZ	6-WDFN	100 V	243 m Ω	3 nC	163 pF

Table 2: MOSFET's with extreme characteristics

R_{DS} due to decreased conduction loss. The switching loss which are related to Q_G and C_{iss} would decrease due to the low voltage rail requirement as investigated in [10]. This effect is also apparent in figure 8 when looking at the low impedance drive situation of 1 Ω . Here the efficiency at lower power levels increase due to decreased switching losses and decrease at higher power levels due to increased conduction losses compared to the 4 Ω drive situation. With an optimized amplifier the efficiency could be improved by the use of different switching devices. Future work should focus on the efficiency optimization of low voltage and high current amplifiers for driving low impedance loudspeakers.

7. CONCLUSION

This work investigate the efficiency of class-D amplifiers driving a low impedance transducer. The motivation is to drive the amplifier and a low impedance transducer directly from a low voltage source such as a battery to obtain a improvement of size, weight, cost and efficiency. An analysis of the peak to RMS voltage of music signals compared to sine wave signals is performed. In combination with a worst case estimation of the power requirement, the DC resistance of the voice coil can be designed given a certain battery voltage. Experimental results on commercial available power supplies and amplifiers demonstrate the advantage of a low impedance transducer in terms of efficiency for battery operated sound systems. Future work will focus on optimization of the amplifier for driving low impedance transducers.

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