Speaker Selection for Class D Output Drivers

INTRODUCTION

Class D amplifiers are a good choice of amplifier when good power efficiency is required, especially at high output power levels. This makes them suitable for use in many battery powered handheld and portable applications. In such applications, small size and reduced component count is also an important requirement, and the opportunity to eliminate output filter components through the right choice of loudspeaker is of great interest to circuit designers. This Applications note provides guidance in the choice and evaluation of loudspeakers suitable for use with Class D amplifiers in portable applications.

FILTER REQUIREMENTS FOR CLASS D

Class D amplifiers generate a PWM signal at their output; the frequency content of this output derives from the amplifier switching frequency together with the underlying audio signal. In an audio application, the output must pass through a low-pass filter to remove the switching modulation and restore the audio. This is sometimes known as the “reconstruction filter”. A variety of different filter configurations may be used; the aim is to pass all audio frequencies and to block all the switching frequencies.

A second-order filter comprising an inductor and a capacitor is highly effective at filtering the high frequency modulation. The second-order cut-off of -12dB/octave results in high attenuation of the switching frequencies. The power dissipated in an LC filter is very low, and the high frequency content in the loudspeaker connection wires is low, avoiding the risk of unwanted radiation and interference, especially from long wires.

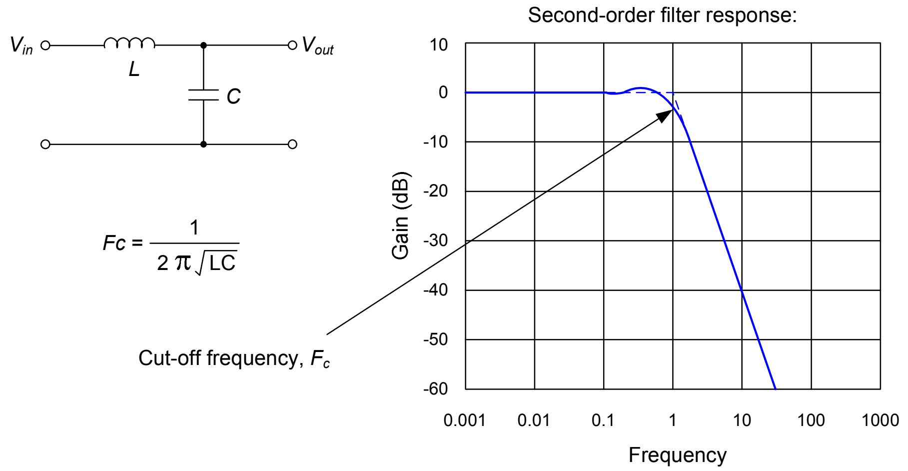

Figure 1 Second-order LC Filter

A first-order filter can be created using either a capacitor or an inductor; example circuits are illustrated. The first-order filter response is -6dB/octave, which delivers less attenuation of the high frequencies, when compared with a second-order filter tuned to the same cut-off frequency. The output filter of a Class D audio amplifier should pass audio frequencies (up to 20kHz) and must attenuate switching frequencies (typically around 700kHz). A first-order filter with a cut-off frequency of 20kHz will provide 30dB attenuation at 700kHz.

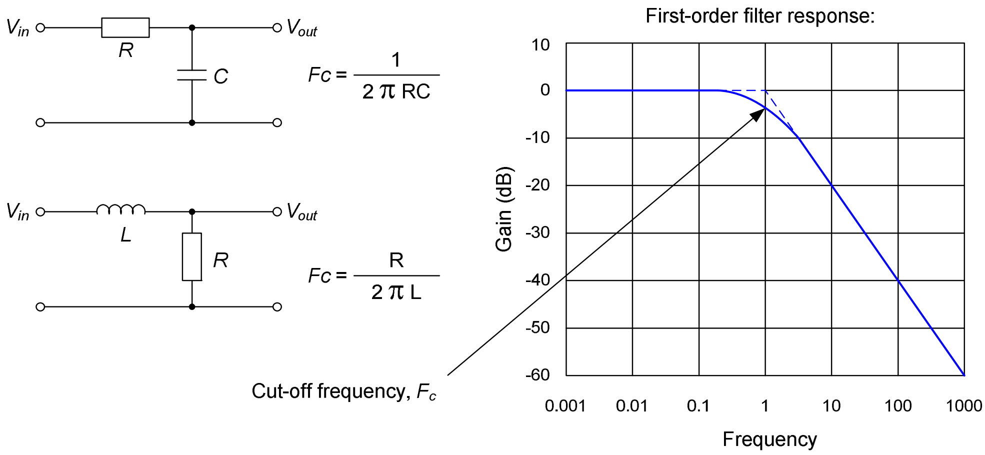

Figure 2 First-order Filters

FILTERLESS OPERATION FOR CLASS D USING LOUDSPEAKER INDUCTANCE

When driving a loudspeaker, it is sometimes possible to take advantage of the loudspeaker's inherent inductance to implement the low-pass filter required by a Class D amplifier output. This reduces the component count associated with implementing the audio reconstruction filter, which is a benefit to miniature handheld applications in particular. The following representation of the loudspeaker illustrates how this works - the series inductance and resistance of the loudspeaker are equivalent to the filter components shown previously.

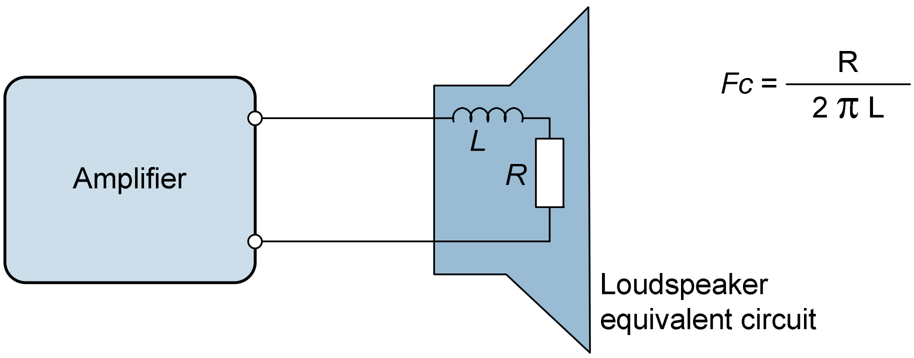

Figure 3 Loudspeaker Equivalent Circuit (simplified)

It follows that choosing a loudspeaker with a suitable inductance is crucial to implementing the 'filterless' Class D output configuration. An 8Ω load with 63µH series inductance will result in a cut-off frequency of 20kHz.

This theory only applies up to a point - in reality, neither the resistance nor the inductance is constant across the relevant range of frequencies. For a Class D audio application, the component's behaviour beyond the 700kHz Class D switching frequency band is of critical importance; for example, it is entirely possible that the impedance of an 8Ω speaker may rise to 200Ω at 1MHz. The explanation for this is that the simplistic model of a loudspeaker is not sufficiently accurate for the purposes of filterless Class D operation. A more detailed equivalent circuit of a loudspeaker is shown in Figure 4.

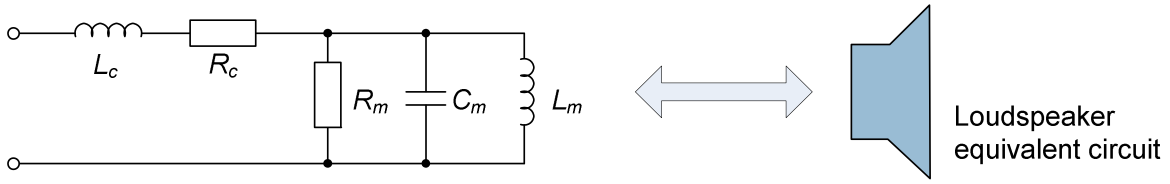

Figure 4 Loudspeaker Equivalent Circuit

Designers must take care to ensure that the filter characteristics of the loudspeaker are sufficiently understood for the intended application. If the loudspeaker does not provide the required characteristics in a filterless circuit, then the power efficiency will be reduced, the audio content may be degraded, and damage to the loudspeaker may occur.

A simpler, but effective, method to assess the loudspeaker suitability is to compare the audio frequency power dissipation with the switching frequency power dissipation in the loudspeaker, and to use this as a guide to the efficiency and effectiveness of the loudspeaker as a Class D filter.

PRACTICAL SELECTION OF LOUDSPEAKERS FOR FILTERLESS OPERATION

The quoted impedance of a loudspeaker is the DC resistance of the voice coil. Typical values for small size loudspeakers are 8Ω or 16Ω. For filterless Class D operation, it is necessary to consider the impedance of the loudspeaker at higher frequencies, up to at least five times the Class D switching frequency. This data must be specifically requested from the loudspeaker manufacturer if not already available. This may look like the data illustrated in Figure 5.

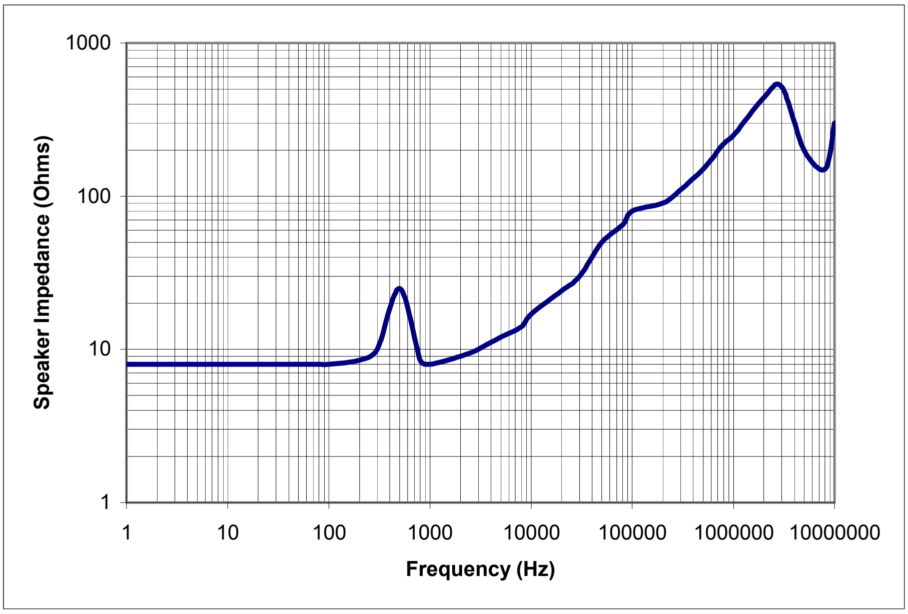

Figure 5 Loudspeaker Impedance vs Frequency

It can be seen from this graph that the loudspeaker has a DC resistance of 8Ω. A smooth, rising impedance characteristic over increasing frequencies is a desirable feature for filterless Class D operation, up to and beyond the switching frequency.

A resonant frequency within the audio band (in this case, at 400Hz) is to be expected; this does not determine the loudspeaker's suitability for filterless operation, though it may affect the audio response in this region. Further resonance characteristics above the switching frequency can be tolerated, provided that the impedance does not decrease significantly below that of the switching frequency. The most significant harmonics of the Class D switching frequency are the 1st, 3rd and 5th harmonics. The impedance of the loudspeaker above the 5th harmonic frequency can usually be disregarded.

The rule of thumb recommended here for choice of loudspeakers is that if the impedance characteristic meets the criteria described above, and the high frequency ripple power dissipation is small compared to the maximum rated power of the amplifier, then there is a good chance that the loudspeaker is suitable. Practical, in-circuit measurements should then be made to verify the power dissipation.

If the impedance of the chosen loudspeaker shows the desirable characteristics described above, then the impedance at the Class D switching frequency should be interpreted from the available data. The Class D output may be considered as the sum of many components, at frequencies above and below the switching frequency; to determine the loudspeaker response to the switching frequency component, the impedance at this frequency is used in the calculation. In the example data illustrated earlier, the impedance at 700kHz is approximately 200Ω.

The amplitude of the Class D output usually corresponds directly to the power supply rails - a 5V supply rail will generate 5V output amplitude. In the case of a BTL configuration, the effective voltage swing across the loudspeaker is doubled, equating to 10V output amplitude. The RMS value of a square wave is half the applicable amplitude. For this example, a 5V RMS shall be assumed.

The current drawn by a 200Ω load can be calculated by applying Ohm's law on the voltage and impedance derived above. In this example, I = V / R = 25mA.

Note that the corresponding power dissipation cannot be determined from these figures, as the phase relation between the voltage and current is not known. The rising impedance characteristic illustrated in Figure 5 is an indication that an inductive component exists, and therefore that a phase difference exists, but it is not recommended to attempt to measure or to interpret the actual inductance for this calculation. The 25mA figure is only a rough indicator of the high frequency dissipation, but is still useable for comparison with the audio frequency dissipation.

At audio frequencies, the loudspeaker impedance is assumed to be equal to the DC coil resistance, eg. 8Ω. The RMS voltage of the full-scale audio signal is the same as that of a sine wave with a peak-peak value equal to the peak-peak Class D waveform. In the example quoted, a 10V peak-peak Class D waveform is the same magnitude as a 5V sine wave, which has an RMS value of 5 / √2 = 3.54V. The current drawn by an 8Ω load can be calculated as above. In this example, I = V / R = 442mA.

The derivation of the applicable RMS voltages for these calculations is shown in Figure 6.

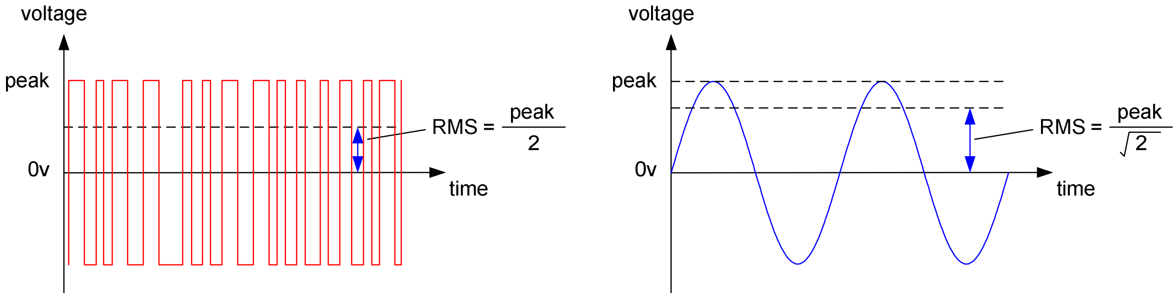

Figure 6 RMS Amplitude of Class D Output - Unfiltered PWM and Filtered Audio Waveforms

If the switching frequency current is a small fraction (eg. <10%) of the audio frequency current, then the filterless configuration is likely to work well, delivering effective filtering and good power efficiency. If the switching frequency current is high, this corresponds to inefficient power losses in the loudspeaker, leading to poor power consumption and a risk that the loudspeaker may suffer damage from the switching frequency energy.

The suitability of the loudspeaker should also be verified by measuring the power consumption of the amplifier, under quiescent signal conditions, with the loudspeaker connected and again with the loudspeaker disconnected. The difference between these two measurements can be interpreted to be equivalent to the power dissipated by the loudspeaker in filtering the Class D switching energy.

Having calculated the high frequency switching energy dissipation, the suitability of the loudspeaker should then be considered in two ways:

Firstly, it should be verified that power rating of the loudspeaker is sufficient to handle the maximum audio power level and the Class D switching energy combined. (For example, if the application is required to deliver 1W of audio, and the Class D switching dissipation is 200mW, then the loudspeaker's power rating must be at least 1200mW.)

Secondly, designers should consider whether the level of Class D switching power dissipation is acceptable in terms of the overall system efficiency and, where applicable, the anticipated battery endurance: if the power efficiency is unacceptable, then it may be possible to select an alternative loudspeaker which offers more efficient filter characteristics.

This practical approach to loudspeaker selection for Class D amplifiers indirectly takes consideration of the loudspeaker inductance but does not make the assumption that the inductance will be fixed across the applicable range of frequencies.

SUMMARY OF CALCULATION / METHOD

For efficient filterless Class D operation, the loudspeaker must provide an appropriate degree of attenuation to the switching frequency components of the amplifier’s output. The recommended method for confirming a loudspeaker’s suitability is summarised in the following four steps.

1. The speaker’s frequency response and power handling capability should be suitable for the audio requirements of the intended application.

2. The speaker impedance vs frequency should be checked for suitable response up to and beyond the amplifier switching frequency.

3. The RMS ripple current at the switching frequency should be calculated from the impedance (at the switching frequency) and from the amplitude of the Class D output signal. This current should be confirmed as being a small fraction of the RMS current of a full-scale audio signal.

4. The power consumption of the amplifier with and without the loudspeaker connected should be compared, under quiescent signal conditions. Taking the difference between these measurements, the Class D switching energy dissipation should be calculated.

5. The Class D switching dissipation should be assessed to ensure compatibility with the loudspeaker power rating (to avoid loudspeaker damage), and to ensure compatibility with the overall system power efficiency (to avoid unacceptable power losses).

CONCLUSION

An appropriate choice of loudspeaker is essential for filterless operation of a Class D amplifier output. If the loudspeaker cannot be relied upon to provide the necessary filtering, then discrete filter components (eg. a second order L-C filter) should be included as part of the circuit design.

Analysis of the loudspeaker’s impedance characteristics, together with in-circuit power measurements is an effective method to select and verify a suitable loudspeaker component for a given application.

With insufficient filtering, there will be a high frequency ripple at the speaker output; this leads to power inefficiency, a risk of damage to the loudspeaker and a likely degradation of the audio reproduction.

Figure 7 shows an illustration waveform in which the loudspeaker current contains a significant level of high frequency distortion; this effect would arise if insufficient filtering exists in the circuit and/or loudspeaker.

Figure 8 shows a reduced level of high frequency distortion, as might exist in a typical ‘filterless’ circuit configuration. It should be noted that Class D switching currents may still be present at the loudspeaker input, even in an effective filterless configuration.

Figure 9 shows the undistorted waveform underlying the signals shown in Figure 7 and Figure 8. In an ideal filterless configuration, the ripple current that is present at the loudspeaker terminals is not present in the audio output, as a result of additional filtering provided by the loudspeaker’s mechanical characteristics.

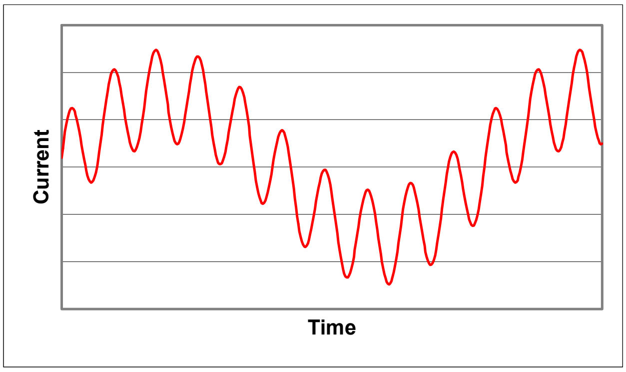

Figure 7 Class D Speaker Current - Inefficient Filtering, Causing Distortion and Power Losses

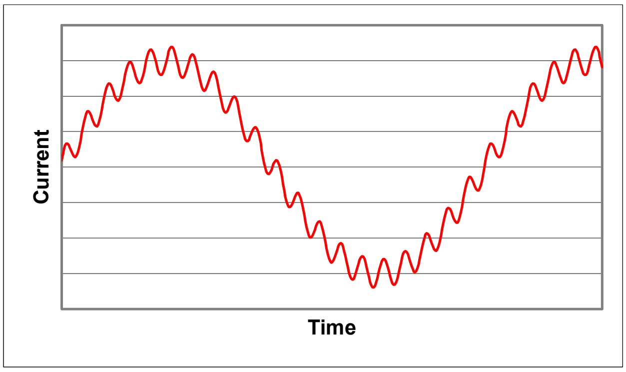

Figure 8 Class D Speaker Current - Switching Currents Filtered Effectively

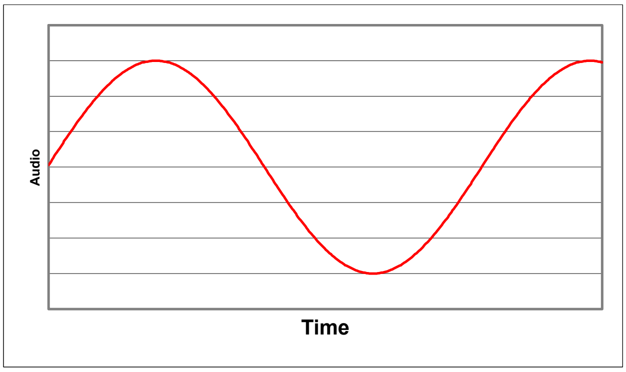

Figure 9 Class D Speaker Output - Switching Effects Eliminated by Loudspeaker Mechanics

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