Passive components for Class D amplifiers

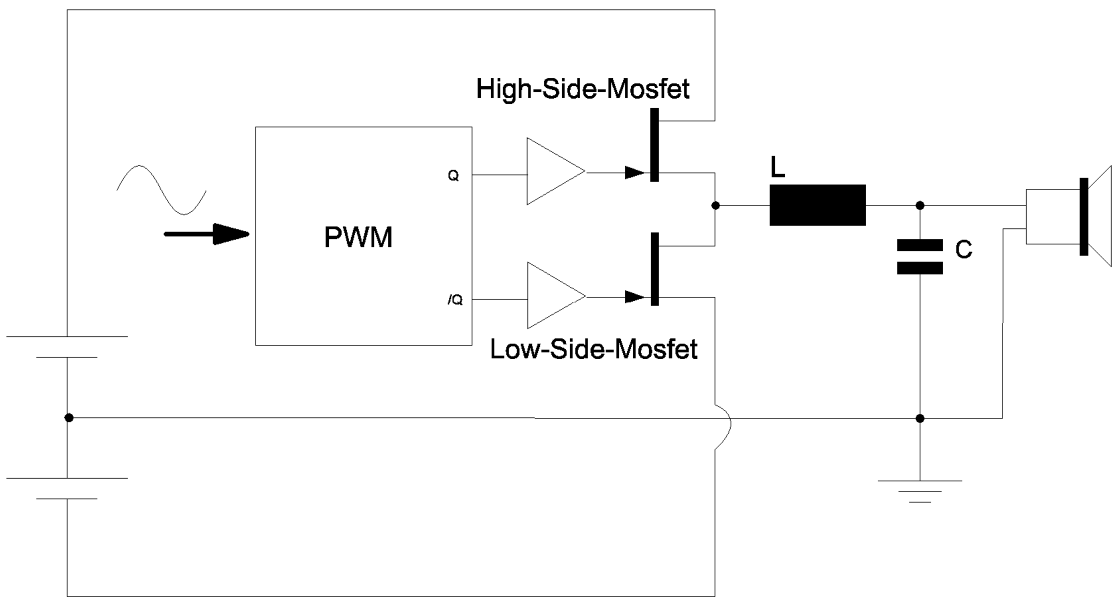
Efficient Amplification

Class D amplifiers have only made headway in audio technology over the last few years, even though this technology has existed since the middle of the last century. This development has been driven by the steady trend towards increasingly miniaturized and high performance devices. High efficiency is of the essence - so MP3 players can run as long as possible and small car radios do not breakdown due to overheating at high power consumption. Analog amplifiers fail to come up to scratch here. As suitable MOSFETs have been on the market a few years now, analog amplifiers are being progressively replaced by Class D. This article firstly examines the basic circuit topologies and then takes a closer look at the design of the Class D filter.

Devices used in modern consumer electronics, especially those in the audio domain, are strongly influenced by digital technology, you only need consider the CD player or the MP3 format. The music files stored on digital storage media are either fed immediately or after conditioning with a digital signal processor (DSP) to a digital/analog converter and the analog signals generated from this module are sent to an audio amplifier with speakers attached.
The use of digital technology is still largely limited to this data storage and digital signal conditioning. To this day, audio signal amplification generally continues to be purely analog. Although digital amplifiers (Class D) have existed since 1958, their use in audio technology has only become interesting recently, since MOSFETs with the required properties have come on the market.
In the meantime, Class D amplifiers have experienced a real boom, because nearly all the major semiconductor manufacturers now offer standard products for them. However, there are still not many passive components for this application area. Würth Elektronik offers a large selection of inductors specially developed and tested for Class D.
Compared with their linear counterparts, Class D amplifiers are subject to significantly lower power losses. In theory, up to 100% efficiency is possible with this type of amplifiers, whereas linear amplifiers attain maximum values of 60% to 70%. The trend is that these Class D amplifiers are gradually squeezing the purely analog AB amplifiers, which still predominate, from the market. Due to the immense advantages in cost, efficiency and package size with comparable audio quality, experts anticipate that there will only be new designs with Class D in a few years to come.

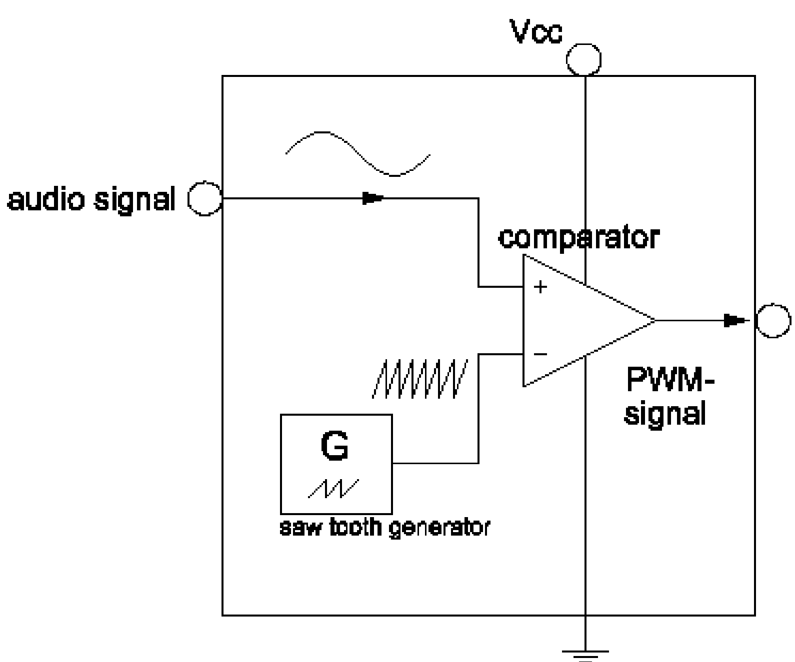
How Class D works

The circuitry of a Class D amplifier is completely different to that of analog versions. Here it is not the analog signal itself that is amplified, but a high frequency sine oscillation, pulse-width modulated with the audio signal, is input at a switching stage (= digital amplifier) and the low frequency component of the amplified signal is then filtered out with a low-pass filter. The Class D amplifier is therefore nothing more than a combination of a pulse width modulator (PWM) and a digital power stage and subsequent low-pass filter. Fig. 1 shows the elements of such an amplifier with analog input in half-bridge topology.



Pulsewidth modulator PWM, high-side MOSFET, low-side MOSFET
Fig. 1: Circuit of a Class D amplifier in half-bridge topology

The PWM block is presented in somewhat more detail in Fig. 2 to better illustrate the function.



Audio signal, comparator, sawtooth generator PWM signal
Fig. 2: Detailed look at the PWM generator

It consists of a comparator, whose inputs are connected with a sawtooth voltage and the audio signal (simplified here as a sine function) (Fig. 3). The comparator compares the two voltages and outputs a digital “1” (full supply voltage V_{cc}) or a digital “0“ (0 V) depending on whether the momentary value of the signal voltage is above or below the momentary value of the sawtooth voltage. The result at the output of the comparator is therefore a rectangular function whose momentary pulse width corresponds to the momentary amplitude value of the audio signal. The information of the audio signal is therefore contained within the pulse width of the comparator output signal – this method is called pulse width modulation.

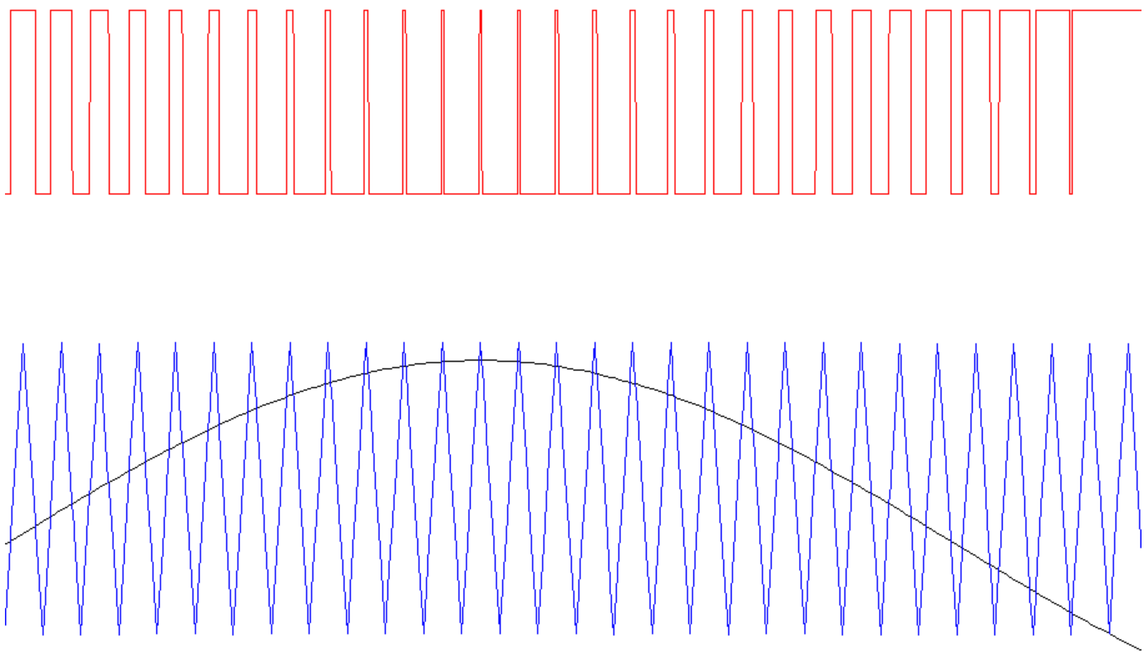


Fig. 3: From the audio signal (black) and the delta voltage from the sawtooth generator (blue), the comparator produces a PWM-modulated signal (red) at the output of the PWM module

This signal, which is now “digital”, drives two MOSFETs in a half-bridge circuit via their respective drivers. The two transistors are driven in counter phase, i.e. the connecting point of the transistors is either at V_{cc} or 0 V. So the digital output signal of the comparator has a higher amplitude so this part of the circuit is the actual “amplifier“.

Configuration	**Impedance of the speaker**	**Standard value for L**	**Standard value for C**
Half-bridge	4Ω 8 Ω	22 µH 47 µH	1.5 µF 0.68 µF
Full-bridge	4 Ω 8 Ω	22 µH 47 µH	1.5 µF 0.68 µF

Table 1: Standard values for the LC filter

As the MOSFETS can switch almost without loss at the switching frequency of a few hundred kilohertz, the efficiency of Class D amplifiers is very high.
The amplified PWM signal is now fed to a low-pass (zero-loss LC network) whose cutoff

frequency is defined such that only the low-frequency audio signal passes to the speaker. After the low-pass filter, the signal has the same shape as the output audio signal, only with a higher amplitude. Similarity with the step-down converter becomes apparent at this point: Linking $-V_{ss}$ with GND and replacing the audio signal with a DC voltage reference V_{ref}, really does produce a DC/DC converter. In principle there are two Class D topologies. The more simple half-bridge circuit was mentioned above. Another common circuit is the full-bridge (Fig. 4). This consists of two half-bridges that feed pulses of opposite polarity to the LC low-pass filter. So there is twice the voltage swing compared with the half-bridge, i.e. four times the power is available at the speaker. The two capacitors connected to ground can also be combined and connect in parallel with the speaker.

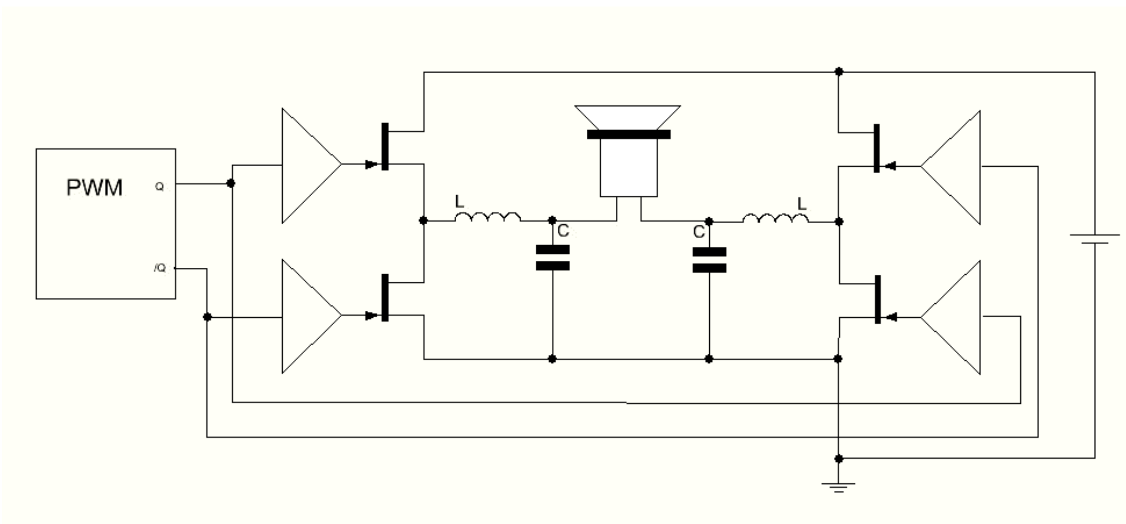


Fig. 4: Circuit if a Class D amplifier in full-bridge topology

Requirements for MOSFETs and drivers

The pros and cons of topologies are easy to summarize: On the one hand, the half-bridge circuit is indeed very simple and fewer MOSFETs (together with drivers) are required. On the other hand, it requires a bipolar power supply with +Vss, -Vss and GND, whereas the full bridge gets by with a power supply with V_{ss} and GND.

There are further differences, such as linearity problems or “bus pumping” (voltage increase effect with $+V_{ss}/-V_{ss}$) for the half-bridge. However, these problems are soluble; the new Class D IC electronics circumvent many problems, which makes life somewhat easier for the developer.

The low power loss for Class D is the ultimate reason for using this type of amplifier in new designs for audio applications. Nevertheless, the demands are significantly higher than for analog amplifiers and therefore represent a challenge for some developers. The semiconductor manufacturers have overcome many of the classical pitfalls with largely integrated Class D ICs, but due to the high currents and high clock frequencies (typically 400 kHz and more), successful Class D design still calls for sound knowledge and a certain experience in the following areas:

- selection of MOSFETs (and drivers insofar as they are not included in the Class D IC),
- selection of passive components for wiring the Class D ICs, especially the selection of suitable capacitors,
- well arranged, HF-capable layout, i.e. ground surfaces where required, sufficiently short low resistance or impedance-controlled PCB tracks, as well as,
- the design of the LC filter and selection of suitable capacitors and inductors.

If the above points are not sufficiently regarded, not only poor sound quality has to be contended with, but also major EMC problems. With the MOSFETs and drivers, the correct

selection of types (self-blocking / self-conducting, PMOS/ NMOS) and the parameters $R_{DS(on)}$ and Q_G are of crucial importance. The forward resistance $R_{DS(on)}$ must be small, as high currents flow and the gate charge Q_G has to be small so the switching times are short and switching losses remain within bounds. The two parameters counteract one another: A small forward resistance automatically leads to a large Q_G value and vice versa. For this reason, the product of $R_{DS(on)}$ and Q_G, also known as FOM (Figure of Merit), is the deciding quality feature of a MOSFET. Only in recent years have MOSFETs arrived on the market with a sufficiently low FOM, such that Class D amplifiers have only now become established on the market.
The following assessment illustrates the situation: Typical gate charge values of high-performance MOSFETs are today of the order of 20 nC and switching times of around 5 ns are achieved. The current flowing into the gate of the MOSFET during a single switching cycle is therefore I = Q/t = 20 nC/5 nS = 4 A. The semiconductor manufacturers offer special MOSFET drivers to satisfy this requirement. The developer now has to use sufficiently wide PCB tracks in the layout regions affected and also place extremely high quality demands on the capacitors for Class D ICs. As small ESL and ESR values are required for blocking capacitors and bootstrap capacitors, mainly high capacitance ceramic capacitors and tantal or polymer electrolyte types are considered. Only the right capacitors provide enough charge quickly to enable high currents.
The high currents are the one problem, short switching times and high switching frequencies of 400 kHz and more, are the other. Every experienced layout specialist knows that this places special requirements on circuit board design. To examine this in more detail would far exceed the scope of this article. References to HF-stable and EMC-compliant circuit board design are to be found in numerous discourses and in the technical literature [1].

Correctly dimensioning the output filter

The output filter is an important part of the circuit, as it is essential in determining the efficiency and reliability of the overall circuit and the resulting sound quality. LC low-pass filters are used for Class D amplifiers, which, in the case of ideal components, are completely loss-free and work without phase shift (Fig. 5).

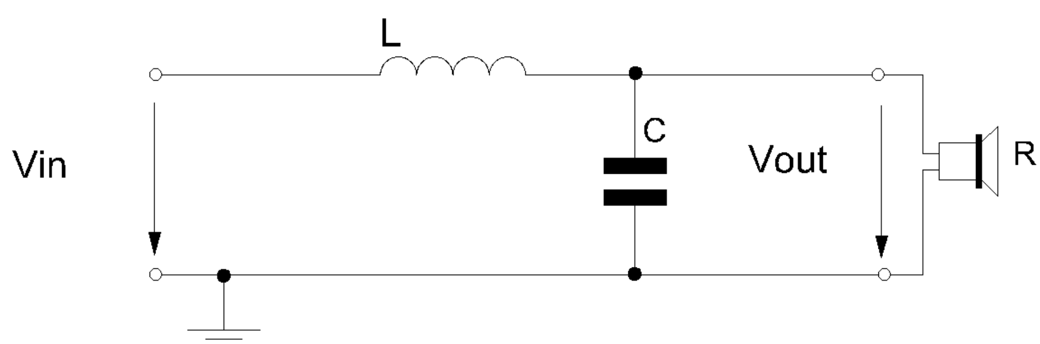


Fig. 5: Circuit diagram of a simple LC low-pass filter

An LC low-pass is, by definition, a second order filter and therefore drops at 40 dB per decade beyond its cutoff point according to $f_{res} = 1/(2\pi \sqrt{LC})$. The cutoff frequency is selected at around 20 kHz to 60 kHz such that it is slightly above the audible range. In contrast to purely RC or RL filter elements, LC networks have a slight resonance overshoot at the cutoff frequency (Fig. 6).

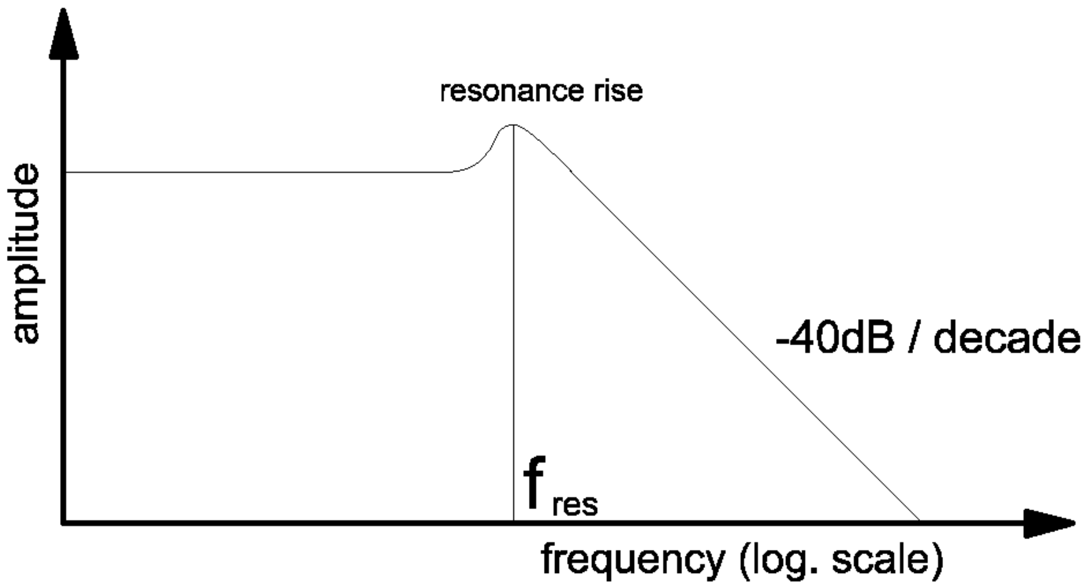


Fig. 6: Bode plot of the LC filters

An important design parameter, which is unfortunately often overlooked, is the impedance of the speaker. Fig. 7 shows the influence of the speaker impedance for a typical Class D filter. It is apparent that this parameter affects both the resonance overshoot and also the phase. As the speaker impedance is an integral part of the filter, this must always be considered in the selection of the filter components. On account of the frequency dependence of the speaker impedance, especially at high frequencies, compensation of the LC output by means of feedback would in fact be necessary. Unfortunately, a sophisticated circuit arrangement would be required here, so that in most designs it is simply omitted at the cost of sound quality. Another problem with Class D designs is EMC. As previously discussed, a poor layout almost inevitably leads to such problems. But the design of the LC filter is also critical: As can be identified from the Bode plot (Fig. 6), the signal amplitude is attenuated above the cutoff frequency, but it is not fully suppressed. Especially at high power, one runs the risks that the high frequency residual ripple on the speaker input lines is too high from an EMC perspective. Good Class D designs often therefore use higher order passive filters.

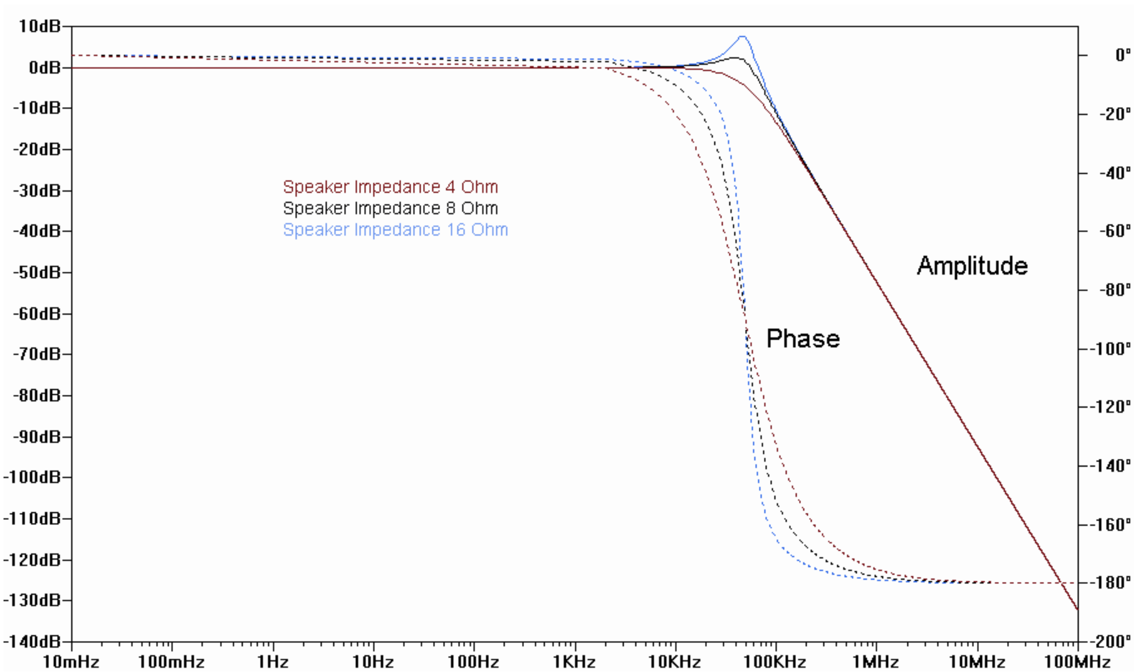


Fig. 7: The speaker impedance affects both the resonance overshoot, as well as the phase of a Class D filter

Calculation of the filter

The following simple considerations help to understand the equations necessary for filter design. Looking at the filter circuit, a voltage divider is identified at which the input voltage and output voltage respond according to the dynamic resistances (see equation (1)). This untidy equation can be converted to (2). Now the Butterworth characteristic is taken for the filter (3) and a comparison of coefficients performed (4), as well as destandardization (i.e. s is replaced with S/ ω). The result is the sought-after equation for dimensioning C (5) and L (6) in a half-bridge circuit. In this equation, L and C stand for the filter elements, R for the load (speaker impedance) and f_{res} for the cutoff frequency of the filter with $f_{SE} = 1/(2\pi\sqrt{LC})$. As expected, the equations reveal that the impedance of the speaker plays an essential role in filter design. These equations apply for a half-bridge circuit. To obtain the equations for the complete full-bridge circuit (Bridge Tied Load, BTL), two half-bridges are joined to form a full-bridge and the resulting capacitances and inductances are combined. This leads to the dimensioning rules for the full-bridge circuit (BTL with capacitor parallel to the speaker) from (7) and (8). As the two inductances are added, the cutoff frequency is of course $1/(2\ \pi\ \sqrt{2LC})$ in this case.
The developer is generally free to choose the limit frequency of the filter so any combinations of LC are conceivable. However, standard configurations are growing and the developer should, if at all possible, keep to standard values from Table 1 in view of the availability of passive components (examples for a cutoff frequency of 20 kHz).

Selection of passive components

Unfortunately, passive components are not ideal; a capacitor comprises not only capacitance, but, on account of its leads, also an inductive and resistive component. The analogous situation applies for inductors. It is crucial to ensure high quality capacitors for Class D filters. This means especially low ESL and ESR values. Ceramic capacitors with X7R or better dielectrics satisfy requirements in most cases; sufficient voltage stability must be ensured. A few basic requirements apply for inductors, such as magnetic shielding and as low a DC resistance R_{DC} as possible. Core materials with low core losses in the switching frequency range of around 400 kHz are essential for high efficiency. Chokes based on iron powder cores (including molded inductors) have very high core losses in this frequency range and are therefore usually unsuitable.

A good compromise between small package size, good saturation behavior and moderate core losses, especially at higher currents, is offered by the alloy powder cores “WE Perm” and “WE Superflux”, which Würth Elektronik uses in its “HC” and “HCA” series. Coils based on ferrite have very low core losses, but a certain package size. These chokes are often used for lower power applications thanks to their value for money. One of the most important parameters for assessing amplifiers is total harmonic distortion (THD). This value is a measure of the distortion of a signal and therefore the audio quality of a speaker. Noise or noise plus interference power is included in the evaluation with THD+N. Because, in contrast with measurement of the pure total harmonic distortion, all factors reducing the sound quality are included, the measurement of THD+N is very well suited as a benchmark for audio devices. The THD+N value is measured with special audio analyzers, a combination of a high quality frequency generator and a spectral analyzer with switchable filters in one instrument. Measurement entails inputting a sinus signal at the amplifier and looking at its output power in relation to the total power spectrum at the amplifier output. As the output power measurement can only be performed in theory over the entire frequency spectrum, it is essential to connect a filter at the amplifier output. Without the specification of filter data (cutoff frequency, bandwidth), specification of THD+N is not meaningful. As the sound quality of amplifiers is strongly dependent on the amplifier (output power) selected and the frequency amplified, discerning tests must be performed at different powers (e.g. at 100 mW, 1 W, 5 W, 10 W) and different frequencies (e.g. 100 Hz, 1 kHz, 5 kHz, 15 kHz). Würth Elektronik had a series of chokes for their Class D whose serviceability was tested by Dr. Ruge, a firm of independent engineering consultants specializing in audio technology. So as to ensure comparability, the output filter in a Class D reference design from a leading semiconductor manufacture was assembled with the appropriate Würth Elektronik inductors. Fig. 8 shows the example of THD+N measurement of a WE-PD series choke (744771133, 1 kHz, 10 W).

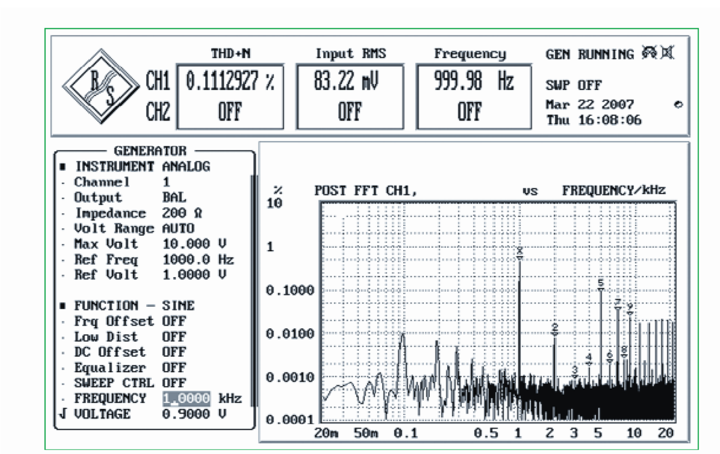


Fig. 8: For a power of 10 W the total harmonic distortion is 0.11% (reference measurement from Dr. Wolfgang Ruge and René Böllhoff, 26.3.07)

The measured THD of 0.11% at the high power of 10 W is very good; the human ear cannot detect this distortion. Table 2 shows a selection of suitable inductors for Class D amplifiers from the Würth Elektronik portfolio. (rh)

Sine power (RMS)	Applications	Suitable series
around 1 W	cell phones	WE-MAPI 3015, WE-TPC 3816, WE-TPC 4818
around 3 W	portable MD/CD/MP3	WE-LHMI 4020, WE-TPC 5818, WE-TPC 5828
around 10 W	smaller TVs, stereos, small devices	WE-PD2SR 7850; WE-LHMI 7050
around 30 W	larger TVs, HiFi	WE-PD 1210, WE-PD 1280,
	Car HiFi	WE-PD 1210
around 50 W to 70 W	DVD 5.1 home theater systems, car HiFi, subwoofer drivers, amplifiers for medium-range power	WE-HCF 2013
over 70 W	Subwoofers, high power amplifiers	WE-HCF 2818

Table 2: Selected inductors suitable for Class D amplifiers from the Würth Elektronik portfolio

Dr. Ing. Ralf Stiehler
Product Manager at
Würth Elektronik
EMC & Inductive Solutions
Telephone +49- 07942/945-0
email: ralf.stiehler@we-online.com
www.we-online.com

Reference

[1] Heinz Zenkner, Alexander Gerfer, Bernhard Rall: “Trilogy of Inductors“; ISBN 3-934350-73-9; also available directly from Würth Elektronik