Linearized Class-D amplifier

Nowadays all analog chip manufacturers do have their own chip-sets for compact and efficient Class-D audio-amplifiers. However, these commercial amplifiers do share one property in common: a pour sound-quality with distortion-levels (THD) not below 0.1 %.
This is mostly due to the old myth that distortion should only origin from analog parts as the PWM-modulator and filters so audio once converted to “digital” PWM should remain undistorted, regarding the lack of output-feedback in many designs.
However, the "amplification" of the PWM-signal in the mosfet-switches is the main cause of distortion. During the few nanoseconds 'dead-time' when both mosfet's are in off-state, the momentary voltage is dependent of many non-linear effects. This distortion can only be fought with a fast feedback from the PWM-output.
The Class-D described here is meant for DIY-audio. With standard components without expensive drivers or modulators, a simple but good amplifier can be constructed.
This relatively simple and small project is complete different from the amplifier LPC1 described else.
As usual in DIY-projects, some parameters as switching-frequency should be tuned after construction with component-values.

Operation

If you place a RC-network in the feedback-loop of an inverting cmos-gate with hysteresis or “Schmitt-trigger”, It will start oscillating. The resulting square-wave at its output can be modulated to PWM by adding a low-frequency-signal to the input of the Schmitt-trigger.
This very simple Schmitt-trigger-type PWM-modulator, I described in July 2005-issue of EWW, can be linearized by adding a huge low-frequency gain in the feed-back loop, while maintaining the low high-frequency feedback for oscillation, realized with with a double integrating opamp. The opamp also adds a linear sawtooth-signal, which linearizes the conversion to PWM in the following cmos-gates.
The circuit is still self-oscillating, like the simple fed-back-Schmitt-trigger type PWM-modulator.
After switching on the supply, at first C12 is charged slowly via R10 till half-supply voltage, before oscillating is started. Hard switching-clicks in speaker are prevented this way.

Frequency-setting

The switching-frequency is set by 3 parameters: The LF-voltage-gain (set by R2 and R1+R3), the ratio between supply-voltage and input-hysteresis of the gate (about 1V), and feedback-delay (set by product R1*C1).
From the PWM-output, via network R2-R1-C1, a triangle-signal is derived (and slightly amplified by opamp), of which the peaks equal the 2 thresholds of te 1st cmos-gate. The opamp adds a low gain of 1.5 to this triangle-signal, so switching frequency and LF-gain can be calculated from R2, R1, C1 and thresholds of 1st gate.
The circuit is tuned for 1 MHz at 12V, for more supply-voltage (and power), the value of R2 should rise proportional to remain switching at 1 MHz. For other supply-voltages with LF-gain remaining at 20 dB, only the frequency should be tuned with C1.
During the peaks of the audio signal (PWM-modulation <20% or >80%) the switching-frequency will drop to 400 kHz by to the increased (dis-)charge time of C1. By this effect the switching-losses are reduced when power is delivered, limiting the dissipation of the mosfet's. The rise in RF-ouput-ripple (till 1Vpp) at peaks is not a problem. By the short duration and frequency-spreading of the ripple the RF-emission will stay below EMC-limits.

Components

The opamp U1 should be a fast, high GBW-type like AD8651 or LT1028, with a bandwidth-product of 50 MHz or more. A slower opamp like NE5534 will rise the distortion.
Output-signal of the opamp is below a few volts pp, so it can be supplied from the lower driver-supply-voltage.

The Schmitt-trigger and driver A1-A4 are fast 74AC14 or NC7WZ14 high current Cmos-gate's.
As driver with a NC7WZ14, 2-3 gates should be placed parallel, with the 74AC14, 4-5 gates.
The input-hysteresis of the 1st gate in oscillator will affect the switching-frequency. It can be tuned with C1.
A small schottky-diode D1 is needed for biasing the P-fet M2, by clamping the PWM.
With a complementary mosfet-pair (M1 and M2) in one SO8-case like Si4532, a maximum output-power of 10W is possible. Maximum dissipation of Si4532 is about 1 W, depending on copper-area at the 4 drain-pins.
For 10W or more, separate N- and P-fets for M1 and M2 in 2 SO8-cases or larger, are recommended.
For more power at lower load-impedance, mosfet's with lower RDS-on should be selected.

The 2 power-inductors L1 and L2 should be wound on a 13mm yellow Iron-powder T50-6 (u=8) toroid, with 34 turns of 0.5 mm Cu-wire. With a red Iron-powder T50-2 (u=10), only 30 turns are needed.
Inductors with ferrite-cores are not recommended, they will add distortion by non-linear permeability.
The capacitors in output-filter C6,C7 should be metal-film, MKT- op MKP-type for linearity.
High-voltage ceramic-X7R for 50 or 100V may also be sufficient.
For minimum RFI-emission all cable-connections should be placed together with the filter-cap's close between ground-plane and cable-connection. If Aluminum caps are used for C13,C14 in supply-lines, extra ceramic cap's of 1uF should be placed in parallel at supply-connections.
The decoupling-caps C9 and C10 should be placed very close to supply-lines of driver and mosfet's.
C1-C4 should be ceramic COG/NPO, all other cap's C5,9,10 are ceramic X7R/ X5R or Y5V.

Results
Power-consumption of the driver is 10mA from the 4V supply. This current is needed for charging the 2 mosfet's with 2 * 5nC in each switching-cycle.
The Idle-power of the output-stage is about 20mA at 16V, 1MHz, due to switching-losses.
Power-efficiency from the output-stage is 90%, at maximum power.
The maximum pp output-voltage is 88% of supply-voltage, resulting in 3.4W at 12V, 6.2W at 16V, or 9.6W at 20V, in 4 Ohms.
At 1 dB lower, at 80% PWM, the harmonic distortion at 1kHz is merely 0.01 % or -80 dB. At 50% (-6dB) and below,THD drops to 0.003%, -90 dB.
Increasing the driver-supply from 4V to 4,5 or 5V will increase the switching-speed of the mosfet's, and lower the “dead-time”, reducing the distortion at the cost of increased idle-power.
The exact driver-supply with these distortion-characteristics and idle-power will be dependent on the threshold-voltage of the mosfet's. When using other mosfet's this driver-voltage may be tuned for setting the dead-time, measured via the idle-power.
Modern power mosfet's do have a lower Rds-on and can also save driver-power by using less gate-charge for switching.
Frequency-response is almost flat from 20Hz to US when loaded with 4 Ohms. At higher or lower loads the response will rise or fall slightly at > 50kHz, for a wider bandwidth at 2 or 8 Ohms, the filter-caps should be adapted.