Unleashing the LM386

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The LM386 must be one of the most popular audio output amplifiers among radio amateurs, despite having been around for a long time. It can be obtained in both dual-in-line and surface-mount packages and outputs 325 mW in the standard version that runs from 4-12 Volts supply voltage. Its voltage gain of 46 dB is in many cases too little, especially in direct conversion receivers. When I built the Pixie 2 with the LM386 audio stage, it struck me how the sensitivity of the receiver was limited by the audio gain. I asked myself if it would be possible to increase the gain and add some filtering without in a simple way, and the result is a gain of more than 70 dB and an audio bandwidth of a few hundred Hz by only adding 3 resistors, 1 capacitor and an inductor.

Analysis of the LM386 Amplifier

The basic LM386 amplifier is used without any feedback between pins 1, 5, and 8. The standard way for getting a larger gain is to connect a large capacitor (say 10 μF) between pins 1 and 8. In either case, the voltage gain equation is:

$$A_{v,1} = \frac{2Z_{1-5}}{150 + Z_{1-8}}$$

Here $Z_{1\text{-}5}$ and $Z_{1\text{-}8}$ are the impedances between the respective pins. This equation describes the feedback path from the output to the emitter of the input stage, where the factor 2 is due to the differential input stage. $Z_{1\text{-}5}$ must also include the built-in 15k resistor which is in parallel to external circuitry, and likewise $Z_{1\text{-}8}$ should include the built-in 1.35k resistor. Thus, without external components, it has a gain of $A_v = 2 \cdot 15k/(150+1350) = 20$ or 26 dB and with a large capacitor between pins 1 and 8 it has a gain of $A_v = 2 \cdot 15k/150 = 200$ or 46 dB.

The application note of the LM386 suggests a bass boost by connecting 10k in series with 33nF between pins 1 and 5 with pin 8 open, while a common set of values among radio amateurs is in the order of 2.2k and 4.7nF. The effect is a roll-off at frequencies above 1-2 kHz. The effect can be analysed with the gain equation above by inserting 2.2e3 + 1/(j2πf4.7e-9) in parallel to the 15k internal feedback resistor. I use Matlab for this kind of analysis.

Additional Gain

The LM386 data sheet says “Gain control can also be achieved by capacitively coupling a resistor from pin 1 to ground.” The effect of a low value resistor here is to decrease feedback and increase gain. JF1OZL has measured the gain with various resistors and by going as low as to a 3.3 ohms resistor, he got 74 dB, see http://www.intio.or.jp/jf10zl/LM386.htm. In this case, the feedback consists of a division between the $Z_{1\text{-}5}$ and the $Z_{1\text{-}gnd}$ impedances, indicating that the gain is found from the equation of an inverting feedback amplifier:

$$A_{v,2} = \frac{A_0}{1 + A_0 \dfrac{Z_{1-gnd}}{Z_{1-5}}} \approx \frac{Z_{1-5}}{Z_{1-gnd}}$$

The approximation is in the case that the open-loop gain, A_o, is much larger than the closed-loop gain, $A_{v,2}$. This will give a gain of 15000/3.3 = 4546 = 73.2 dB which is close enough to JF1OZL’s measurement. Such a high gain requires careful circuit layout with attention to ground loops and proper decoupling, or the amplifier will oscillate. I have measured a gain of over 80 dB in a well-decoupled circuit, but then the amplifier is at the verge of self-oscillation.

High Gain and Filtering

The two ideas above can be combined in order to get both a high gain and high frequency roll-off. Further, if the circuit between pin 1 and ground is a series resonance circuit, the bandpass characteristic can be made even sharper. An inductor of 1 mH will resonate with the 100 μF capacitor at about 500 Hz and is fine. The problem now is that the gain will drop so much at the higher frequencies that it gets below the value of 9 which is the stability limit for the LM386. To limit the attenuation at high frequencies, the inductor has to be paralleled with a resistor and a value of 220 ohms or less seems to be adequate. A potentiometer in series with the inductor makes the gain variable. The resulting schematic is shown in Fig. 1.

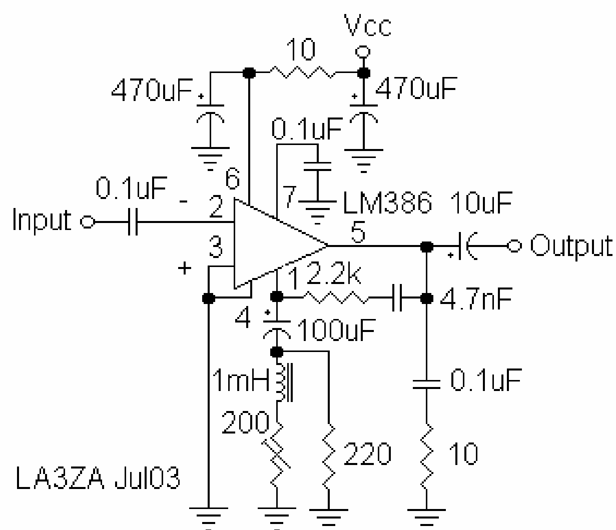

Figure 1. LM386 with enhanced gain and filtering

Measurements

Measurements were made for this circuit with an LM386-N1 with date code 99 from National Semiconductors at a supply voltage of 9 Volts, no output load, and no input coupling capacitor. In this circuit, the DC resistance of the 1 mH inductor of about 2 ohms, and the equivalent series resistance of about 0.5 ohms of the 100 μF capacitor play a role and must be accounted for. The upper curve is with no series resistance except for those of the inductor and capacitor, the middle curve is with a total resistance of 10 ohms, i.e. 10-2-0.5=7.5 ohms series resistance, and the lower one is for the pot at its maximum value of 200 ohms.

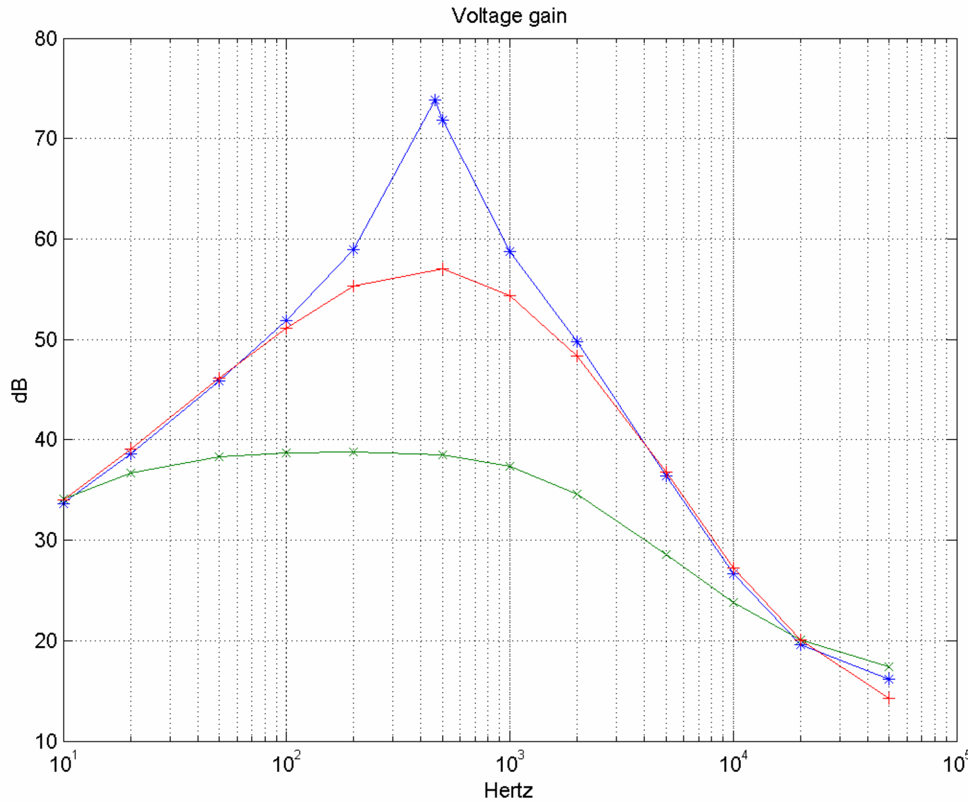

Figure 2. Measurements with R = 2.5, 10, and 200 ohms

Discussion

I tried different LM386-N1's in this circuit and found that the peak gain of the highest curve would vary. Another chip with date code 99 gave 2 dB more gain, while a third one with date code 92 had 7 dB lower gain. I also tried a surface mount LM386-M1 dated 93 which had 5 dB less gain. In all cases, the gain at 1 kHz hardly changed at all. Also, the peak gain is sensitive to output load. The peak value of the highest curve would fall by 8 dB with a 32 ohm load, while hardly changing at all at 1 kHz. These results suggest that the gain, $A_{v,2}$ depends on the open-loop gain, and that the open-loop gain varies from batch to batch.

The muting of the amplifier by means of pin 7 (SPRAT no. 113, Winter 2002/3, pp18-20), is still possible, but only if pin 7 is connected to Vcc. Grounding of pin 7 will only mute the amplifier in the basic 26 and 46 dB circuits, while the amplifier of Fig. 1 will instead output a low-level low frequency noise.

I also tried to find the gain equation for the circuit in Fig. 1 and my guess was $A_v = A_{v,1} + A_{v,2}$. However, this equation overestimates gain by something like 8 dB except for the peak of the highest curve. Maybe some readers who are more into the inner workings of this amplifier can come up with a better equation.

In summary, addition of a few components to the basic LM386 amplifier results in a response which is fine for CW reception with a peak in the 500 Hz range. The amplifier also has enough gain for a direct conversion receiver with a passive mixer like the Pixie 2, that it in many cases it can drive a loudspeaker. Hopefully, the circuit can benefit other direct conversion receivers also.