A new stereo enhancement circuit for class-D amplifier

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Abstract: This paper presents a novel stereo enhancement structure for the surround stereo class-D audio amplifier. The principle of this stereo enhancement scheme has been analyzed. It shows that the amplifier with this proposed circuit have a better live effect than the traditional class-D audio amplifiers. In this circuit, the input audio signal from one channel can be amplified in the two channels at the same time, by a way of cross-coupling. The ratio of gains in the two channels also can be adjusted by changing the external resistance, which improves the stereo effect. A practical implementation in a CMOS 0.18-μm process has been done to validate the theoretical results. When a sine signal with 1 KHz frequency and 100 mV amplitude is applied in one channel, and a DC applied signal in the other, the amplifier demonstrates a gain difference of 9.4 dB.

Keywords: Class-D amplifier, stereo enhancement, cross-coupling, ratio of gains, CMOS

Classification: Integrated circuits

References

1 Introduction

As the portable consumer electronics are increasingly digitized, the class-D audio power amplifier gradually gets into this field by replacing the conventional class-AB audio power amplifier for its high efficiency, low power consumption and good heat dissipation [1]. The stereo technique distributes an audio signal to two independent sounds in two separated channels, and there are some differences of the delay and intensity between the two sounds [2, 3]. These differences include the location and direction information of the original signal, which makes them sound like in the original spot [3]. However, in the portable application, the short distance between the left and right speakers makes the delay and intensity difference unobvious, thus the stereo effect is seriously weakened [6]. In order to restore the immersive and realistic sonic impression, some stereo enhancement technique should be taken.

This paper proposed a novel and sample cross-coupled stereo enhancement circuit for the class-D audio amplifier. Compared with the conventional class-D audio amplifiers, it can provide a good stereo restoring solution for portable device with the low cost and easy integration.

2 Principle of proposed stereo enhancement

a. Principle of the conventional stereo restoring

One solution [1] is to process the two audio signals in the different channels respectively with the complex filter-matrix, which makes left ear hear the sound only from the left speaker, and right ear hear that of the right. But this method should use a digital filter with the complicated structure and algorithm, and that is not suitable for the device’s miniaturization and low cost. Another solution is to use ADC and DSP to sample and process the audio signal [2, 3, 6], then amplifies and restores the audio signal. The conventional solution with ADC and DSP to enhance the stereo is shown in Fig. 1 (a). Due to the use of ADC and DSP, the size and cost of the chip is increased greatly. The references [4, 5] propose two filterless structures, but they have no stereo effect if the input audio signals are the same.

![Fig. 1](image-url)
When the signals are exactly the same from the two speakers, the listener do not feel there are two sound sources, instead sounds like a signal from the midpoint between the two speakers. This point, which does actually not exist, is called the virtual audio-image. The Fig. 1 (b) shows this case. Two signals respectively from the two speakers overlap and then reach human ears, which results in the location of the virtual audio-image. That means the sound heard by each ear contains the components from both of the two speakers. In the stereo restore system, by adjusting the delay or intensity difference of the signals between the two speakers, the virtual audio-image will locate on a certain point close to one of the speakers from the midpoint.

b. Technology of cross-coupled stereo enhancement

The principle of the cross-coupled stereo enhancement is shown in Fig. 2. The input signal in left (or right) channel is coupled with the signal in the other channel by the resister $R_2$ after it is amplified by the pre-amplifier (C-AMP) in this channel. So that the final output signal from left (or right) channel contains the components from both of the two channels. It is mean that the input signal of one channel will be amplified simultaneously in the two separated channels. By adjusting the gain of the C-AMP and coupling coefficient, the input audio signal from the one of channels will be amplified in the two separated channels with the different gains. So, the intensity difference of one source between the two channels can make the virtual audio-image move along the medial-axis, which results in the virtual audio-image being close to the left (or right) side. Then the stereo effect is produced.

As shown in Fig. 2, for easy deducing, assume that only one channel (L, e.g.) has an input signal $V_{inl}$, and $V_{ol1}$ is the output of this input signal through the C-AMP in the L channel by the first time, which can be written as Eq. (1)

$$V_{ol1} = V_{inl} \times \left( -\frac{R_3}{R_1} \right)$$

The output signal $V_{ol1}$ is coupled to the input terminals of the C-AMP in R channel by the resistor $R_2$, and then amplified by the C-AMP in R channel. Suppose that $V_{or1}$ is the output of the C-AMP in R channel after
the \( V_{oi1} \) first through the amplifier. \( V_{or1} \) can be express as Eq. (2). It is also coupled to the input terminal of the C-AMP in L channel by resistor \( R_2 \), and amplified by the C-AMP in L channel again.

\[
V_{or1} = V_{oi1} \times \left( -\frac{R_3}{R_2} \right) = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left( -\frac{R_3}{R_2} \right)
\]  

(2)

Suppose that \( V_{oi2} \) is the second amplified output, and then we can get Eq. (3).

\[
V_{oi2} = V_{or1} \times \left( -\frac{R_3}{R_2} \right) = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left( -\frac{R_3}{R_2} \right)
\]

(3)

\[
V_{inl} = \lim_{n \to \infty} \sum_{i=1}^{n} V_{oi1} = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left[ \sum_{i=0}^{n} \left( -\frac{R_3}{R_2} \right)^{2i} \right]
\]  

(4)

As this coupling amplification process continuous cycle, we can assume that the signal amplified by the C-AMP in L channel for the Nth times is \( V_{oln} \), and the signal amplified by the C-AMP in R channel for the Nth times is \( V_{orn} \). And so on, they can be described as Eq. (4) respectively.

\[
V_{oln} = V_{or(n-1)} \times \left( -\frac{R_3}{R_2} \right) = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left( -\frac{R_3}{R_2} \right)^{2n-1}
\]  

(5)

In actual cases, the iteration times can be regard as infinite, So that the final output of the \( V_{inl} \) in L channel can be described as Eq. (6).

\[
V_{OL} = \lim_{n \to \infty} \sum_{i=1}^{n} V_{oi1} = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left[ \lim_{n \to \infty} \sum_{i=0}^{n} \left( -\frac{R_3}{R_2} \right)^{2i} \right]
\]  

(6)

To ensure the stability of the system, we need \( R_3/R_2 < 1 \). So Eq. (6) can be changed as Eq. (7).

\[
V_{OL} = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left[ \lim_{n \to \infty} \frac{1-(R_3/R_2)^{2n}}{1-(R_3/R_2)^2} \right] = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \frac{R_2^2}{R_2^2-R_3^2}
\]  

(7)

In the same way, the final output of \( V_{inl} \) in the R channel is Eq. (8).

\[
V_{OR} = \lim_{n \to \infty} \sum_{i=1}^{n} V_{ori} = V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \left[ \lim_{n \to \infty} \sum_{i=1}^{n} \left( -\frac{R_3}{R_2} \right)^{2i-1} \right]
\]

\[
= V_{inl} \times \left( -\frac{R_3}{R_1} \right) \times \frac{-R_2 \cdot R_3}{R_2^2-R_3^2}
\]  

(8)

After an input signal of one channel (L) is passed through the cross-coupled stereo enhancement structure, its gains in this channel (L) and the
other channel can be described respectively as $A_{VL}$ and $A_{VR}$. Therefore, in the two channels, the ratio of the gains of the audio signal from L channel can be written as Eq. (9).

$$
\frac{A_{VL}}{A_{VR}} = \frac{V_{OL}/V_{inl}}{V_{OR}/V_{inl}} = -\frac{R_2}{R_3}
$$

(9)

From Eq. (9), it can be obtained that the audio signal will be amplified in both two channels simultaneously regardless to it is applied to which channel. The ratio of the gains, which is the difference of the sound intensity in two channels, can be implemented by adjusting the ratio of $R_3$ and $R_2$.

In the Fig. 2, the transfer function of the cross-coupled structure and the $-3$ dB bandwidth of the C-AMP can be express as Eq. (10). There is one pole $p=-1/R_3C_1$ in this structure.

$$
\frac{V_o}{V_{in}} = -\frac{R_3}{R_1} \frac{1}{1 + R_3C_1S}, \omega_{-3\text{dB}} \approx \frac{1}{2\pi R_3C_1}
$$

(10)

In order to prevent the signal distortion, we can make $100 \text{ KHz} \geq \omega_{-3\text{dB}} \geq 20 \text{ KHz}$, by adjusting the capacitance of $C_1$ and resistance of $R_3$. The noise, which is out of the sound band (higher than 20 KHZ) can be filtered.

c. Structure of the pre-amplifier

The main part of the C-AMP is a fully differential transconductance operational amplifier as shown in Fig. 3. It is designed as a two-stage folded cascode operational amplifier for the high gain. The common-mode feedback circuit is constituted by the PM11 ∼ PM14, NM7 ∼ NM10, R2 and C2. The $C_1$ is the miller-compensation capacitor, and the resistor $R_1$ is to regulate the zero of this amplifier.

3 Experimental results

This part shows the simulation results of the proposed circuit based on the SIMC 0.18 $\mu$m COMS process. The Fig. 4 shows the frequency response of the C-AMP. The simulation result shows that, when a 5 pF capacitor is connected the output as a load, the DC gain of the transconductance
Fig. 4. The frequency response of the cross-coupled structure

Fig. 5. The simulation results of the stereo enhancement amplifier is up about to 83 dB, the phase margin is about 78°, and the −3 dB bandwidth is about 25 KHz.

A sine signal with frequency of 1000 Hz and amplitude of 100 mV is applied to the left channel, while only a common DC voltage (1.6 V) is applied to the right channel. The supply voltage is 3.3 V. As shown in Fig. 5, the blue line is the differential input signal of the L channel, the purple line is the differential output of the L channel and the red line is the differential output of R channel. The peak-to-peak voltage of the L channel differential output is 2.893 V, and that of the R channel is 1.684 V. The gain difference between the two channels is about 9.4 dB. The result proves that the intensity difference is obtained by the proposed stereo enhancement structure. On the condition of 3.3 V supply, 3 Ω load and the THD+N=1%, the output power is about 2.0 W and the efficiency of the class-D amplifier is more than 90%. Fig. 6 shows the micrograph-photo of the 2.1 channel stereo class-D with the proposed circuit. The area size of the proposed circuit is only about 0.24 mm², and the whole die area is about 3.2 mm².

4 Conclusions

A novel stereo enhancement circuit has been proposed and implemented in a 2.1 channel class-D amplifier by the SMIC 0.18 μm CMOS process. An input audio-signal, applied in any channel, will be amplified with different gain ratios in the two channels by the way of cross-coupling. The difference of
the two outputs could change the location of the virtual audio-image, which makes the stereo effect enhance. It is shown by the simulation results that a gain difference of 9.4 dB is obtained and the stereo enhancement structure can work as expected. The proposed circuit can be directly used in the two-channel class-D audio amplifier mentioned in references [4, 5] to improve the stereo performance almost without increasing the chip and application cost.

Fig. 6. The micrograph-photo of the class-D Die

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