Ripple Feedback Filter Suitable for Analog/Digital Mixed-Mode Audio Amplifier for Improved Efficiency and Stability

Nam-In Kim, Sang-Hwa Jung, Ji-Yeoul Ryoo and Gyu-Hyeong Cho
Korea Advanced Institute of Science and Technology (KAIST)
373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
E-mail: poem2u@mail.kaist.ac.kr

Abstract — A new ripple feedback filter is presented for Analog/Digital mixed-mode amplifier (MMA) among audio applications. MMA is composed of two amplifiers: one is analog amplifier responsible for high fidelity and the other is digital switching amplifier in charge of high efficiency. To improve both total harmonic distortion (THD) and efficiency, passive RLC filter is needed at the output side of the digital switching amplifier. Conventional filter, however, causes phase delay, which worsens current loop stability and makes the normal operation of MMA impossible. Ripple feedback filter is newly suggested to solve this problem, obtaining excellent efficiency and low THD.

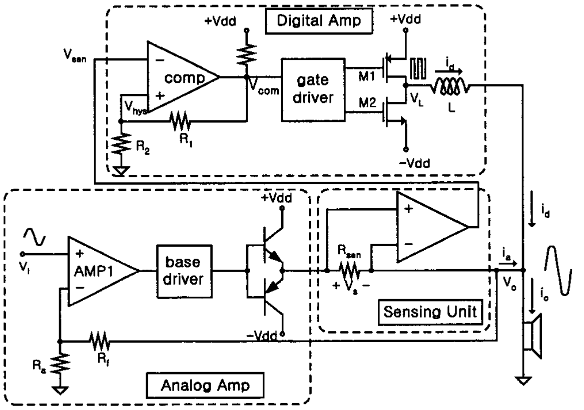
I. INTRODUCTION

Over the last several decades, there have been various kinds of amplifiers studied for audio applications that are so familiar with human's life. Conventional analog amplifiers such as class A, class B and class AB have very excellent distortion characteristics, but show considerably poor power efficiency and bulky volume for cooling. So in order to keep pace with the recent tendency of miniaturization and energy saving, audio power amplifier technology applying class D so called digital switching amplifier is getting growing interest[1]. But in spite of excellent efficiency, since digital amplifier has relatively poor fidelity characteristic, most recently an analog/digital mixed-mode amplifier (MMA) has been reported[2].

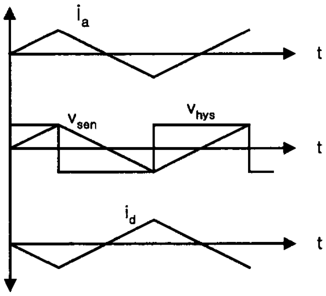
II. BASIC MIXED MODE AMPLIFIER

An MMA is obtained by combining analog amplifier with digital amplifier so as to have the merits of both analog and digital amplifiers, high fidelity as well as high efficiency. A basic MMA version and its basic operation are shown in Fig.1(a) and Fig.1(b), respectively. In Fig.1(a), MMA is composed of an analog power amplifier and a digital switching amplifier, and analog amplifier plays a role of independent voltage source with voltage gain responsible for high fidelity. On the other hand, digital amplifier is in charge of high efficiency and works as a dependent current source to supply most of the current needed in the load.

The principle of operation is very simple and clear. There exist two switching states in digital amplifier. The first state is M1 (PMOS) turn-on and M2 (NMOS) turn-off state. The second switching state is vice versa.



(a) Basic mixed mode amplifier block diagram



(b) Switching operation of basic mixed mode amplifier

Fig.1 Basic mixed mode amplifier

0-7803-7262-X/02/$10.00

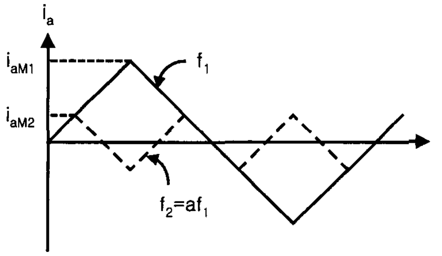


Fig.2 Analog ripple current according to switching frequency

When input voltage Vi increases, analog current i_a and therefore V_{sen} also increases because the output V_{sen} of sensing unit in Fig.1(a) is proportional to analog current i_a. When V_{sen} reaches the upper hysteresis voltage $+V_{hys}$ of the comparator, PMOS switch at the digital amplifier output stage is turned on and NMOS is turned off. This is the first switching state. In this state, analog current i_a begins to decrease and it also decreases V_{sen}. After a while if V_{sen} reaches the lower hysteresis voltage $-V_{hys}$, the switching state is changed from the first state to the second (PMOS off and NMOS on). The following operations in the second switching state work in opposition to those of the first state. Through such a procedure, the digital amplifier is controlled to minimize the output current of analog amplifier so that most of the load current is supplied from the digital amplifier. As a result analog amplifier merely supplies analog current i_a with inverse phase to the ripple component of digital current i_d to compensate the distortion caused by the digital amplifier.

In MMA without ripple filter such as Fig.1(a), the ripple component of digital current i_d and analog current i_a are inversely proportional to switching frequency as shown in Fig.2. Since the analog amplifier absorbs or supplies current to get rid of switching ripple component from digital amplifier, its operation is accompanied with somewhat power loss and heat in analog amplifier, which can be expressed as follows:

$$P_a = \frac{Vdd \cdot I_{aM}}{2} = \frac{Vdd^2}{8Lf_{sw}} \equiv K_a \cdot \frac{1}{f_{sw}} \qquad (1)$$

where Vdd is one of two power supply voltages providing ±Vdd, I_{aM} is peak analog current assuming the triangular waveform, L is output inductor in digital amplifier and f_{sw} is switching frequency. As shown in eq(1), since the analog amplifier loss P_a is inversely proportional to the switching frequency while digital switching loss P_d is directly proportional to switching frequency, the total power loss P_{idle} in idle state can be expressed as follows:

$$\begin{cases} P_d = K_d \cdot f_{sw} \\ P_a = K_a \cdot \dfrac{1}{f_{sw}} \end{cases}$$

$$P_{idle} = P_d + P_a = K_d f_{sw} + K_a \cdot \frac{1}{f_{sw}} \ge 2\sqrt{K_d K_a} \qquad (2)$$

where P_d and P_a are the switching loss in digital amplifier and analog amplifier loss, respectively. P_a, P_d and P_{idle} are expected to have a tendency like the graph shown in Fig.3. From eq(2), we know that the switching frequency f_{sw} should be selected so that P_a equals to P_d to minimize idle power loss P_{idle}, i.e., $2\sqrt{K_d K_a}$.

But it is quite difficult to increase sufficiently the switching frequency at where P_a equals to P_d because of driving high power switch components. Although it is successfully achieved to drive the power switches at high frequency, MMA still dissipates some power loss correspond to $\sqrt{K_d K_a}$, which can be quite large according to an output inductor and power supply voltages.

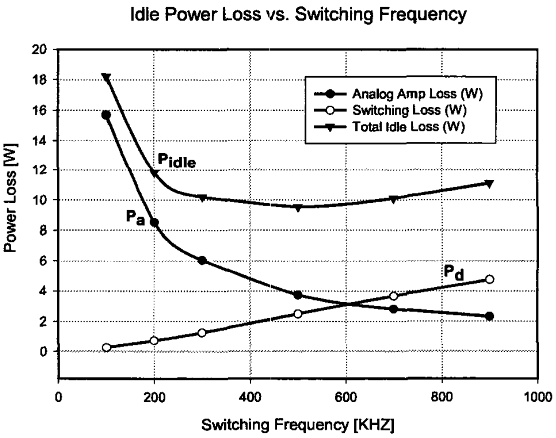
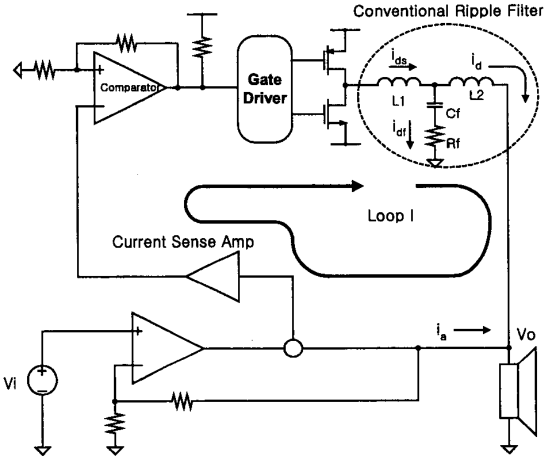


Fig.3 Idle power loss according to switching frequency

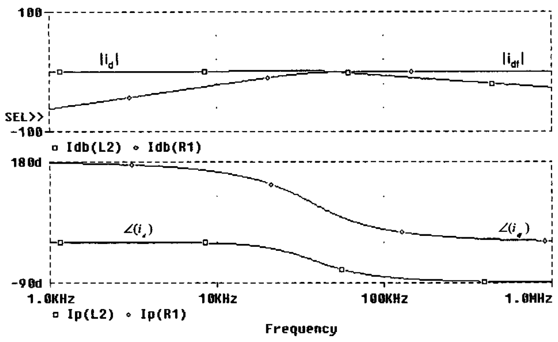
III. CONVENTIONAL RIPPLE FILTER

As another way to reduce the total power loss in idle state described previously, we can insert a ripple filter as the conventional manner as shown in Fig.4(a). Fig.4(b) shows the frequency response of the conventional ripple filter inside the dotted circle of Fig.4(a). Fig.4(b) shows that the switching frequency above several hundreds kilo-hertz can make the ripple component of i_d less and therefore both the analog current i_a and the analog amplifier loss P_a also lower.

In applying the conventional ripple filter to MMA, there, however, is one serious problem. That is the phase of i_d and therefore that of i_a is additionally delayed by the ripple filter. The phase delay of i_a means that the phase margin of loop gain along the loop I shown in Fig.4(a) is worsen and makes MMA unstable. If the loop I is unstable or has the insufficient phase margin, it will be impossible to drive MMA at the high frequency. It goes without saying that it is impossible the higher order filter to be applied to MMA.



(a) MMA schematic adopting conventional ripple filter



(b) Frequency response of ripple filter

Fig.4 Conventional ripple filter and its frequency response

IV. PROPOSED RIPPLE FEEDBACK FILTER

In order to improve stability problem related to phase delay by the ripple filter, a ripple feedback filter with a new structure is presented in this paper as shown in Fig.5. The main feature of the presented structure is that i_{df} of Fig.4(a) is used as information in Fig.5 to control digital amplifier instead of being filtered through ground. By doing so, the stability problem related to phase delay by the ripple filter can be improved significantly.

If L1 is much larger than L2, i_{ds} and the sum of i_{df} and i_d become triangular waveform as in the case of no ripple filter, and V_{sen} has no phase delay. In order to prove it, let the gain K of i_a be the same as that of i_{df}, then the current sense amplifier output V_{sen} can be obtained as follows:

$$V_{sen} = K(i_a - i_{df}) = -K(i_d + i_{df}) = -K \cdot i_{ds} \tag{3}$$

As mentioned above, because i_{ds} is triangular waveform having no additional phase delay by ripple filter, V_{sen} has no phase delay, either. Since i_{df} is utilized as switching information for digital amplifier, no additional phase delay is expected along the loop II shown in Fig.5. Although much smaller analog current i_a is supplied in the form of sinusoidal wave with phase delay in order to compensate ripple current i_d, the current sense amplifier output V_{sen} appears not in the form of sinusoidal waveform but triangular similar to the case of no filter. In brief, though analog current i_a is supplied with phase delay, there is neither the effect of delay at V_{sen} terminal nor any stability problems.

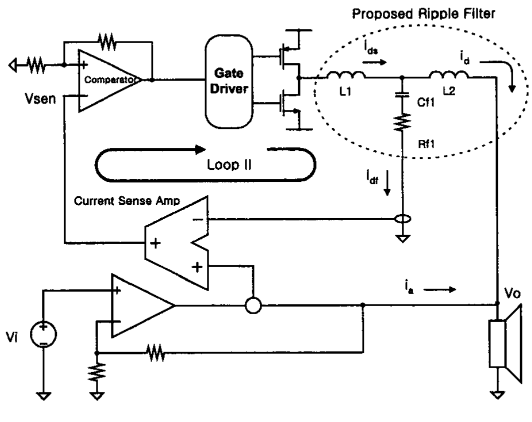


Fig.5 Improved MMA with the proposed ripple feedback filter

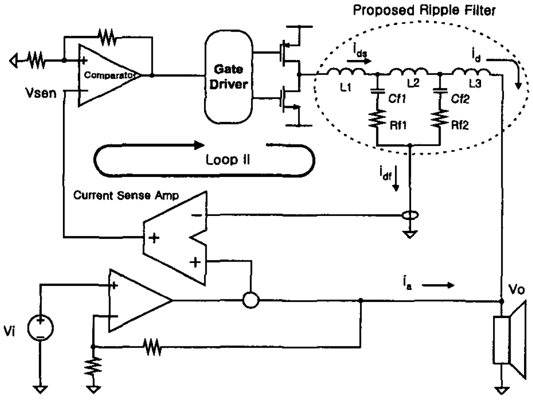


Fig.6 Improved MMA with two stage ripple feedback filter

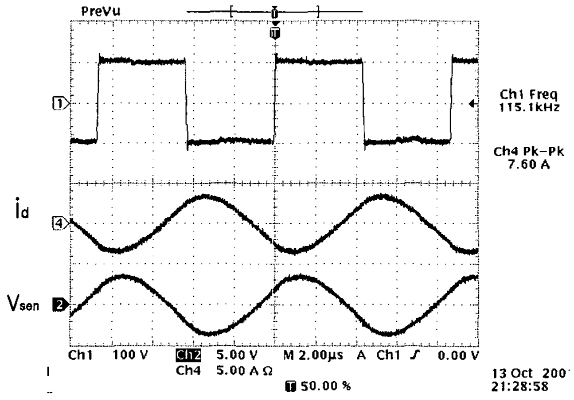
In addition to using the ripple filter as one stage as shown in Fig.5, we can also adopt the higher order ripple filter, for example, as two stages as shown in Fig.6. In Fig.6, in spite of adopting the third order filter that is higher order than in Fig.4(a), MMA is expected to have no problems in stability. In applying the proposed ripple feedback filter, another good point is that by just modifying the comparator and the current sense amplifier properly, no additional components are required as compared with the conventional ripple filter.

As a result, analog power loss P_a is decreased enough to be negligible by means of the ripple feedback filter and THD becomes much lower, because analog amplifier merely supplies much smaller analog current i_a than that of MMA with conventional filter.

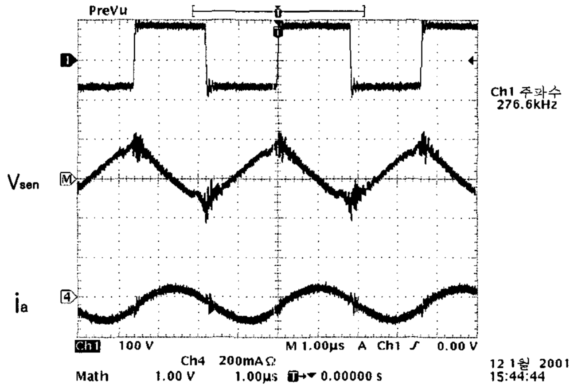
V. EXPERIMENTAL RESULTS

A prototype audio MMA having a rated power of 2kW (1kW per channel) is built for the purpose of Live Concert and tested successfully. Experimental waveforms of 2kW MMA are shown in Fig.7 and Fig.8. The supply voltages ±Vdd are set to ±100Vdc, and L1, L2 and L3 are 50uH, 5uH and 5uH, respectively. Switching waveforms in idle state for conventional ripple filter and proposed ripple feedback filter are shown in Fig.7(a) and Fig.7(b), respectively.

In the case of using second order ripple filter simply bypassing the ripple current to ground in conventional manner as shown in Fig.4, the maximum f_{sw} was possible below at most 115kHz as shown in Fig.7(a) because of phase delay.



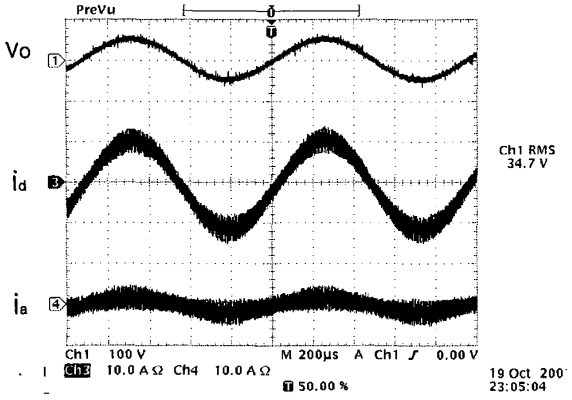
(a) Conventional ripple filter
(upper:100V/div, middle:5A/div, lower:5V/div)



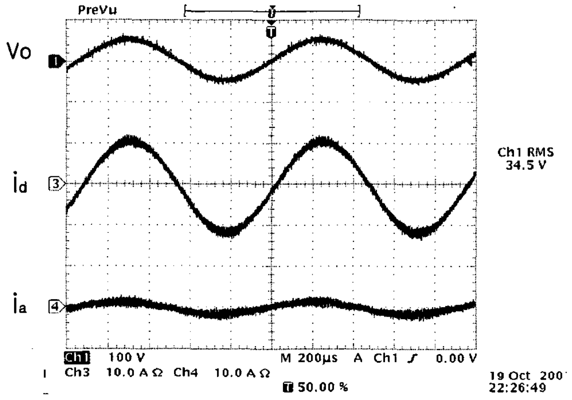
(b) Proposed ripple feedback filter
(upper:100V/div, middle:1V/div, lower:200mA/div)

Fig.7 Switching waveforms in an idle state

And such an insufficient switching frequency caused much larger ripple current and higher P_{idle} rather than no ripple filter. Therefore the measured results for such a case are excluded here. On the contrary, in Fig.7(b) for the proposed ripple feedback filter such as Fig.5 or Fig.6, although i_a shows the delayed sinusoidal waveform, by being summed with i_{df}, V_{sen} is similar to triangular waveform and switching operation is still stable. From Fig.7, we can see that analog ripple current is decreased and therefore P_{idle} will become much lower. The experimental waveforms for the proposed ripple filter are compared with those for the basic MMA having just one inductor in Fig.8. Fig.8(a) and Fig.8(b) show the experimental waveforms for the basic MMA and MMA with proposed ripple feedback filter, respectively. From these figures, the ripple components of i_d and i_a in Fig.8(b) are much smaller than those of i_d and i_a in Fig.8(a) for the basic MMA.



(a) Basic MMA with no ripple filter
(upper:100V/div, middle:10A/div, lower:10A/div)



(b) Improved MMA with the ripple feedback filter
(upper:100V/div, middle:10A/div, lower:10A/div)

Fig.8 Comparison between Basic MMA and Improved MMA

In Fig.9, the idle power loss is compared between the basic MMA and the improved MMA adopting the proposed ripple feedback filter. From this figure, we can see that idle power loss is reduced to 40% (40W) of that (100W) of the basic MMA when switching frequency is selected around 300kHz. Because the analog power loss P_a is dominant between P_a and P_d when the switching frequency is under about 300kHz, idle power loss curves in Fig.9 are inversely proportion to the switching frequency. If much higher frequency is achieved, idle power loss can be decreased a little more.

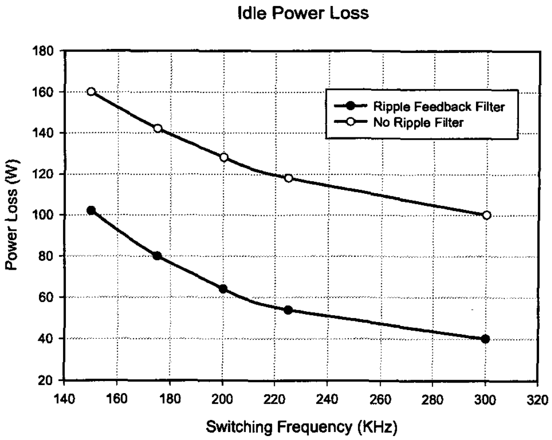


Fig.9 Idle power loss versus switching frequency

VI. CONCLUSIONS

A new ripple feedback filter suitable for mixed mode amplifier is presented in this paper. It is usually difficult and unnatural to adopt the conventional ripple filter in MMA because of its bad influence upon stability. By using the proposed ripple feedback filter, however, we can freely design multi-stage filter without regard to stability and phase delay. In MMA with the proposed filter, power loss is reduced to about 40% of the basic MMA. We think that the proposed ripple feedback filter can be used in the other applications, combining analog with digital switching circuits.

References

[1] H.R. Camenzind, "Modulated Pulse Width Audio Power Amplifier", IEEE Trans. On Audio and Elect., vol.AU-14, NO3, Sep.1966, pp136-140

[2] Nam-Sung Jung, Nam-In Kim and Gyu-Hyeong Cho, "A New High-Efficiency and Super-Fidelity Analog Audio amplifier with the aid of Digital Switching Amplifier: Class K Amplifier", IEEE PESC'98, pp457-463, 1998