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Comparison of PWM Modulation Techniques for Digital Power Amplifers

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1. Introduction

Earlier work [1,2] has shown that interpolative noise shaping techniques make PWM more suitable for high quality Digital Power Amplification. (See Fig. 1.) Oversampling the input to a pulse width modulator reduces the nonlinearity inherent to the PWM process, while noise shaping the input can reduce its wordlength with no deterioration of audio band signal quality. This, in turn, reduces modulator clock speed making the modulator more practical to build. In [2] we have described the performance of software simulations for most of the various types of PWM except so-called 'two sample consecutive' PWM. Here we concentrate on this type of modulator with the aim of making a broad comparison of the major PWM configurations. We begin with a brief description of each modulation type considered and continue by examining their performance and relative ease of construction.

2. Major PWM Configurations

PWM is, in general, a process whereby information-bearing signals are represented (at least in part) as variations in the width of high frequency pulses. PWM schemes may be divided into two broad categories: two level, 'AD' type modulation or three level, 'BD' type modulation. With the latter, the sign of a given input sample determines the *polarity* of the corresponding PWM pulse. In either case, however, we may choose to modulate one or both edges of the PWM pulse as is shown in Fig. 2. In two sample consecutive PWM the position of each pulse edge in time is a function of *different* sample values. Each two sample consecutive PWM pulse can be thought of as a combination of two 'sub-pulses' on either side of the regular timing marker with the width of each sub-pulse corresponding to the value of one of two adjacent input samples. (It should be noted that, for reasons of increased power switch complexity, we consider only type AD two-sample consecutive PWM.) As implied above, and as shown in Fig. 3, there is only *one* pulse for every two input samples. Two-sample consecutive PWM stands out as it is the only PWM configuration we have considered where the pulse repetition frequency, F_{pr} is different from the input signal sampling frequency, f_c. (In this case $f_{pr}=\frac{1}{2}f_c$.)

In all types of PWM the levels of harmonic distortion are functions of the sampling frequency, ω_c, the signal frequency, ω_0, and the modulation depth, M. In [2,3] we have shown that simple but accurate approximations for the levels of harmonic distortion associated with some of the PWM variants can be derived easily. They are, in fact, functions of:

$$r=\frac{M\omega_0}{\omega_c} \quad \text{and} \quad \theta=\frac{\pi\omega_0}{2\omega_c}+\frac{\pi}{2} \qquad (1,2)$$

and have been reprinted in Table 1.

Table 1: PWM Distortion Level Approximations

modulation type	F_2/F_1	F_3/F_1	F_4/F_1	F_5/F_1
AD single sided	$1.51r$	$3.51r^2$	$9.73r^3$	-
AD double sided	$1.51r\cos\theta$	$0.88r^2\frac{\sin 3\theta}{\sin\theta}$	$1.22r^3\frac{\sin 4\theta}{\sin\theta}$	-
BD double sided	-	$3.51r^2$	-	$29.73r^4$

3. Interpolative Noise Shaping

An interpolative noise shaper is a device which uses feedback around a quantizer to frequency shape quantization error. It accepts a finely quantized b bit input and produces a more coarsely quantized b' bit output. When the input to the noise shaper is sufficiently oversampled, it is possible to retain that high b bit resolution over the audio band with only the b' bit output at the expense of raising noise power at frequencies above the audio band. So, for a given SNR requirement, noise shaping permits a reduction in signal wordlength at the expense of additional circuitry operating at a high sampling rate. The size of the reduction is a function of the oversampling factor and the filter used in the noise shaper feedback loop. Here we use a a third order filter of the form:

$$H(z) = 3z^{-1} - 3z^{-2} + z^{-3} \qquad (3)$$

to reduce the wordlength from 16 to six bits (assuming a 16X oversampled input).

4. Implications for PWM

In general, noise shaping helps to make an audio quality (type AD or BD) pulse width modulator more practical to build by reducing the rate at which it must operate. The clock speeds associated with b' bit AD and BD modulators preceded by b' bit third order noise shapers operating at various f_c are shown in Table 2.

Table 2: Modulator Clock Rates

f_c (kHz)	b'	AD Rate (MHz)	BD Rate (MHz)
176.4	12	722.5	361.3
352.8	9	180.6	90.3
705.6	6	45.2	22.6

The combinations of noise shaper wordlength and sampling frequency have been chosen to give roughly the same effective SNR as 16 bit quantization with no oversampling. The rates quoted for AD and BD modulators are applicable to all the specific AD and BD modulation types respectively. The factor of two reduction in clock rate for the BD modulators is, of course, because part of the information contained in an input sample is reflected in the polarity (i.e., in the *amplitude* domain rather than the *time* domain) of the corresponding BD PWM pulse.

5. Investigations

The simulator described in [1] has been expanded to generate single and double sided class BD PWM waveforms so that full comparisons between all the specific AD and BD modulation types considered is possible. The noise shaper has also been expanded to operate with a third order filter in its feedback loop. Fig. 4 shows the complete block diagram for the power amplifier. (It should be noted that the non-idealities of the power switch are not included in the simulation.) We shall compare the effects of varying the frequency, f_{u}, amplitude, M, and sampling rate, f_c of a single, noise shaped, tone input to the AD and BD modulators.

6. Results

The output tone spectra for the various types of AD and BD PWM are shown in Fig. 5. Parts (a) through (d) have been reprinted from [2]. The input to each modulator is a 16 bit, 16 times oversampled, near full scale, 2kHz tone first passed through a third order noise shaper to reduce the wordlength to 6 bits. These four plots imply that the *single sample*, single sided and double sided AD modulators exhibit odd and even order harmonic distortion while the single sample, single sided and double sided BD modulators exhibit only odd order harmonic distortion.

Comparison of PWM Techniques

Part (c) displays the output spectrum for two sample consecutive AD PWM. Comparing this with the others, we immediately notice something unusual; the noise floor is significantly higher. This problem is currently being investigated and an explanation along with a solution, if possible, will be reported in future publications. In the meantime, we note that when more bits are retained from the output of the noise shaper (i.e., more than are required to preserve 16 bit signal quality) the noise level decreases. Fig. 6 shows the tone spectrum of a two sample consecutive modulator preceded by a *eleven* bit third order noise shaper. While this would be less acceptable from an implementation perspective, we may still compare the modulation types. So for the time being we clearly see a distortion term at 6kHz while also noting the *absence* of the even order distortion term at 4kHz.

The remaining experiments show the effect of varying signal frequency, f_0, signal level, M, and sampling rate, f_c for two sample consecutive AD PWM along with regular double sided AD and BD PWM. (Due to the poorer relative performances of single sided modulators, we no longer consider them as realistic options.) Fig. 7 shows how, for a f_0=2kHz, M=0.90, tone input, harmonic distortion levels fall for increasing f_c. Perhaps the most interesting thing to note here is the strong similarity of the performance of two sample consecutive AD PWM to that of two sided BD PWM. They both, of course, differ from two sided AD PWM by exhibiting only odd order harmonic distortion. The first harmonic distortion term levels for double sided AD PWM follow those of two sample consecutive AD PWM and double sided BD PWM quite closely with the former some two or three dB lower than the latter two. However, the level of the second double sided AD PWM distortion term is larger than, and falls much slower than, that of the other two. With 16X oversampling, all the distortion terms for all the modulation types are nearly (or fully) beneath the quantization noise floor.

Fig. 8 summarizes the results of a similar set of simulations, this time with a 5kHz input. The pattern is the same as that in Fig. 7, but, as is always the case with PWM, harmonic distortion levels rise with signal frequency.

Next, Fig. 9 shows how harmonic distortion levels vary with signal amplitude. Here it is interesting to note that as M is reduced, the BD and two sample consecutive AD distortion levels fall more rapidly than the double sided AD levels and actually become lower than these levels for M<0.50. So for lower signal levels two sample consecutive AD and double sided BD modulators perform better than the double sided AD modulator. As explained in [2], this effect is accounted for by the fact that the double sided BD and the two sample consecutive AD distortion terms fall with higher powers of M than those associated with double sided AD modulation.

Lastly Fig. 10 presents the results of a 'DIN' type intermodulation distortion test performed on the three modulators. A 250Hz and an 8kHz tone in amplitude ratio of four to one are sampled at 705.6kHz. In all cases the intermodulation products are centred about the 8kHz tone and its second harmonic at 16kHz. Again, the performance of the two sample consecutive AD modulator is very similar to that of the double sided BD modulator. Although both of these perform slightly better in this test than the double sided AD modulator, all three modulators seem to possess quite low level intermodulation distortion.

7. Conclusions

Perhaps the most interesting immediate result of these experiments is the similarity of two sample consecutive AD and double sided BD PWM. Both of these modulation types have an additional degree of freedom over double sided AD PWM. (In double sided BD PWM we use *pulse polarity* to convey information and in two sample consecutive PWM we use *both edges* of the pulse to convey information.) As a consequence, both these modulation types exhibit only odd order harmonic distortion as compared with double sided AD PWM which exhibits odd and even order harmonic distortion.

However, since under some conditions the performance of double sided AD modulator was somewhat better than that of the other two modulation types while under other conditions the converse was true, it is reasonable to regard all three modulation types to be of 'comparable' performance. There are, however, potentially serious disadvantages associated with two of these modulation types. Specifically, while the double sided BD modulator has the advantage of lower clock speeds, a three level power switch will be significantly more difficult to build than a two level switch. Furthermore, while the two sample consecutive AD system would not have this problem, this modulation type does suffer from the noise floor problem explained in Section 6.

In summary, the final conclusions we can draw from these experiments as to a clear preference for one modulation type over another are restricted somewhat by exactly which factors will be the most critical limitation for a hardware implementation of the PWM power switch. For this reason, it is felt that future work should now concentrate on *full* hardware prototype implementations for the double sided AD and BD and two sample consecutive modulation AD types (along with work addressed toward solving the noise floor problem associated with a two sample consecutive modulator preceded by a noise shaper). This work would help to expose which practical limitations place the strictest constraints on overall performance. To this end a double sided/two sample consecutive AD modulator is being constructed [4]. This will be used in conjunction with a second order noise shaper interfaced with a real time audio source. Past this, the construction of an AD power switching stage is of prime importance.

8. References

[1] J.M. Goldberg & M.B. Sandler: "The Application of Noise Shaping for an All Digital Audio Power Amplifier", presented at The 87th Convention of the Audio Engineering Society, 1989, New York, preprint no. 2832.

[2] J.M. Goldberg & M.B. Sandler: "New Results in PWM for Digital Power Amplification", to be presented at The 89th Convention of the Audio Engineering Society, 1990, Los Angeles.

[3] J.M. Goldberg & M.B. Sandler: "Noise Shaping and Pulse Width Modulation for an All Digital Audio Power Amplifier", a manuscript currently under review with The Journal of the Audio Engineering Society.

[4] R.E. Hiorns, R.G. Bowman, J.M. Goldberg, M.B. Sandler: "Developments in Realising an All Digital Power Amplifier", to be presented at the 90th Convention of the Audio Engineering Society, 1990, Paris.

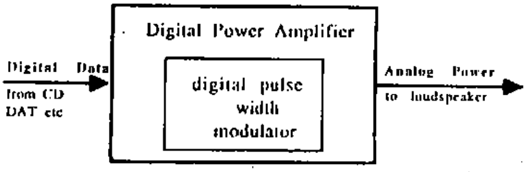

Fig. 1: Digital power amplification

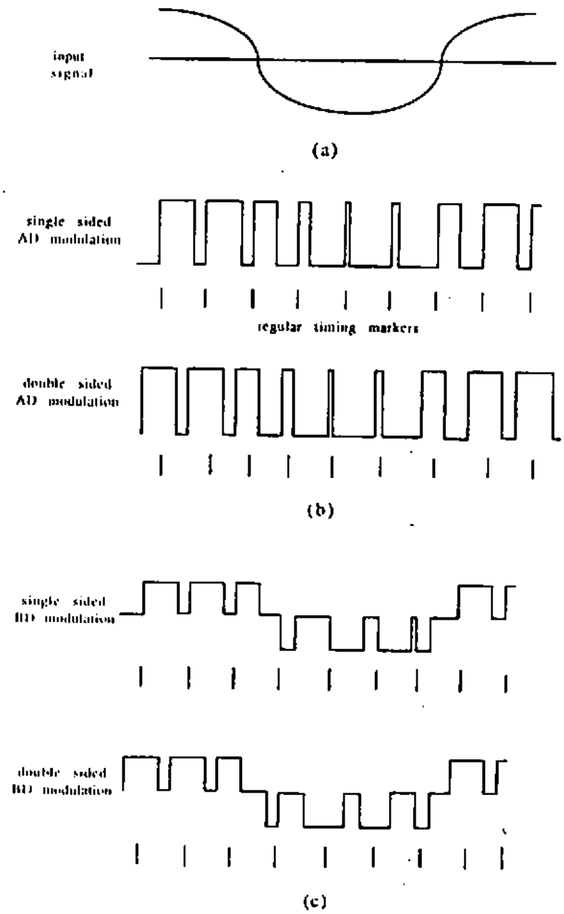

Fig. 2: Pulse Width Modulation Schemes
(a) input; (b) class AD modulation;
(c) class BD modulation

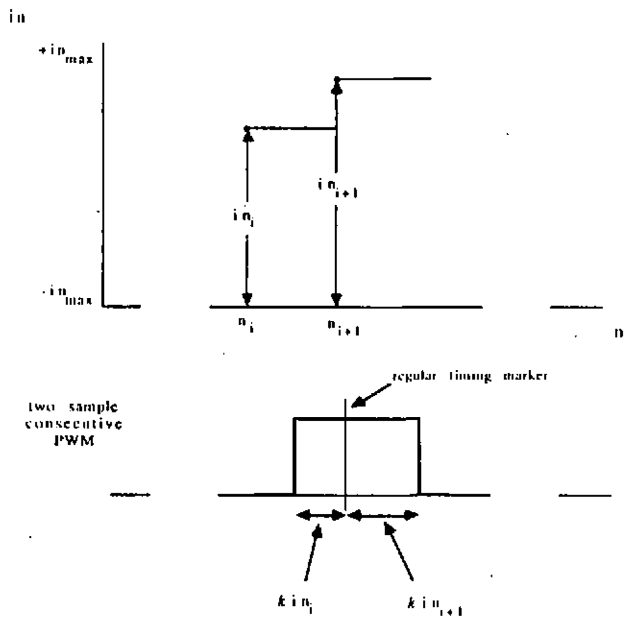

Fig. 3: Two Sample Consecutive AD PWM

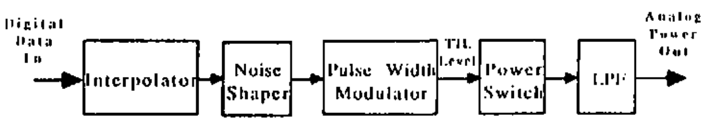

Fig. 4: Digital Power Amplifier Block Diagram

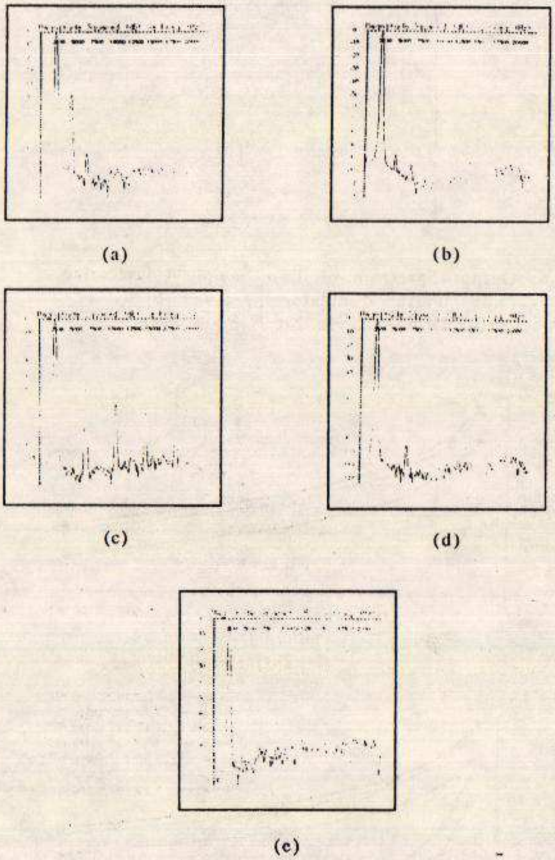

Fig. 5: PWM Output Spectra

(a) single sided AD, (b) double sided AD
(c) single sided BD, (d) double sided BD
(e) two sample consecutive AD

Fig. 6: Output Spectrum of Two Sample Consecutive Pulse Width Modulator preceded by Third Order, Eleven Bit Noise Shaper

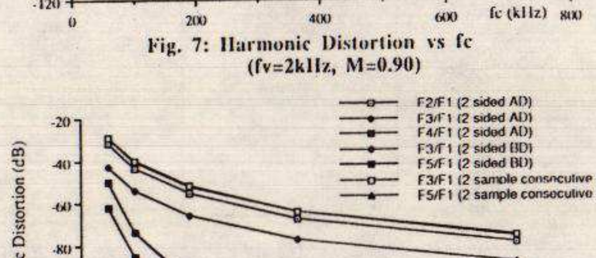

Fig. 7: Harmonic Distortion vs fc
(fv=2kHz, M=0.90)

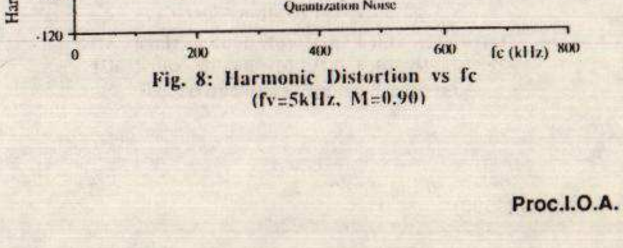

Fig. 8: Harmonic Distortion vs fc
(fv=5kHz, M=0.90)

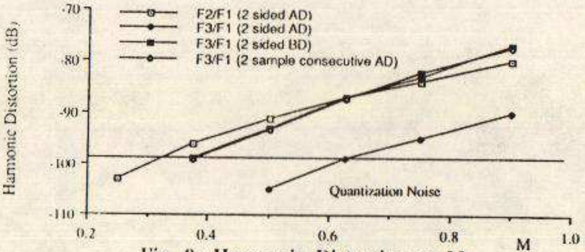

Fig. 9: Harmonic Distortion vs M (fc=705.6kHz, fv=5kHz)

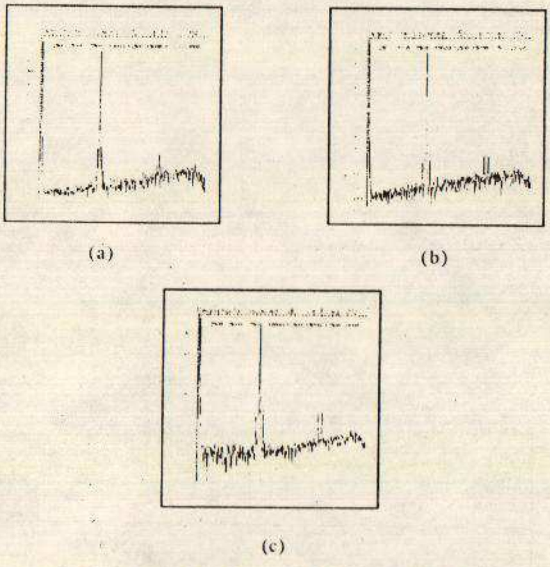

Fig. 10: Intermodulation Distortion Test Results
(a) double sided AD, (b) double sided BD
(c) two sample consecutive AD