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Simple, Ultralow-Distortion Digital Pulse Width Modulator

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ABSTRACT

A core problem with digital Pulse Width Modulators is that effective sampling occurs at signal-dependent intervals, falsifying the z-transform on which the input signal and the noise shaping process are based. In a first step the noise shaper is reformulated to operate at the timer clock rate instead of the pulse repetition frequency. This solves the uniform/natural sampling problem, but gives rise to new non-linearities akin to ripple feedback in analogue modulators. By modifying the feedback signal such that it reflects only the modulated edge of the pulse train this effect is practically eliminated, yielding vastly reduced distortion without increasing complexity.

1. INTRODUCTION

Digital pulse width modulators are commonly used to drive H bridge output stages in power D/A converters (commonly referred to as “digital amplifiers”). Although the use of analogue controlled modulators with feedback is more warranted in this line of work, the present analysis highlights problems which occur equally in analogue and digital modulators. Digitally implemented, the level of complexity is not higher than that of the simplest prior art methods, while offering performance well beyond that available from the most complicated designs known to date. Academic interest aside, the new work could have applications in small-signal D/A conversion.

2. TERMINOLOGY AND DEFINITIONS

PWM	Pulse Width Modulation, Pulse Width Modulated, Pulse Width Modulator
NTF	Noise Transfer Function (noise shaper analogue of Error Transfer Function)
DC	(prefix) That which can be fully characterised using a time-invariant stimulus
f_s	Audio input sampling rate. f_s=48kHz unless stated otherwise.
f_r	The PWM pulse repetition frequency. f_r =8f_s unless stated otherwise
f_c	The PWM timing clock. Defines the timing resolution of the PWM signal.

3. HISTORY

In the eyes of the DSP engineer, the most obvious way of obtaining a high-quality analogue signal capable of driving a loudspeaker would be digitally generating a pulse-width modulated data stream based on PCM audio signals and "amplifying" this using a switching power stage (invariably assumed to be perfect). During the 90's this idea has led to numerous efforts to design the best possible PCM-to-PWM conversion algorithm.

3.1. f_r sampled method

The basic structure assumed by most modulators is that of an upsampling filter followed by a counter circuit.

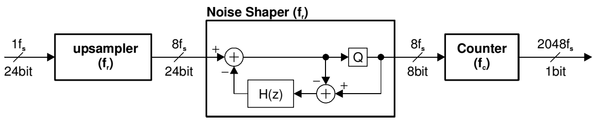

Figure 1: Basic f_r sampled noise shaped PWM generator

A noise shaper is inserted to ally realistic counter rates (f_c) with good in-band noise performance. Error-feedback noise shapers execute very efficiently in DSP, consisting of no more than an FIR filter, an addition and a truncation. The counter circuit can be made either to modulate one edge or two edges. Single-edged PWM signals offer a theoretical advantage over double-edged PWM in that any asymmetry between rise and fall times of the analogue waveform does not lead to errors. In reality, the variation of edge shape with output current is far greater than the symmetry error.

It was quickly realised that this algorithm is not ideal because the output is sampled at signal-dependent instants while the input is sampled at regular intervals. This effectively constitutes a variable delay or phase modulation. Phase-modulating a signal with itself generates distortion that becomes worse at higher signal frequencies. The problem is not limited to the signal. The shaped HF noise is subjected to the same nonlinearity and part of it demodulates into the signal band. A result of this is that higher orders of noise shaping actually worsen SNR performance.

Modulating both edges greatly reduces distortion by having two sampling instants moving in opposite directions, but the distortion is still significant, at least in "digital" terms. In fact, a double-sided "naïve" modulator already has sufficient performance for the system THD+N to be dominated entirely by any practical power stage – a fact that had obviously escaped the attention of the digital PWM vanguard.

Plot 1 (in annex) shows the spectrum out of a simple 4th order noise shaper. Plot 2 shows the spectrum produced by a single edged modulator processing the signal of plot 1 while plot 3 shows the double edged variant. The double edged variant has significantly better distortion and noise performance than the single edged variant. Either way, the low-frequency spectrum is still largely plastered over by demodulated HF noise.

3.2. Improved f_r sampled method

In a first improvement [1], the low-frequency error is corrected by predicting what the continuous-time equivalent of the input signal would be at the resulting PWM sampling instant. In effect, the 8fs PCM signal is pre-distorted in such a way that the modulation distortion is cancelled.

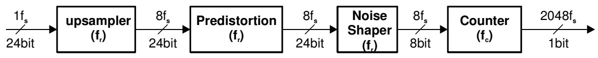

Figure 2: noise shaped PWM generator with predistortion.

Distortion products can be rendered arbitrarily small. The demodulation of shaped noise introduced by the PWM modulation is not addressed though. Not correcting for the demodulation of shaped noise turns the design of the noise transfer function into a delicate balancing act, as detailed in the same paper.

3.3. f_r sampled method with error model in the noise shaper

Both errors can be addressed simultaneously if the error introduced by the PWM process is placed inside the noise shaper loop.

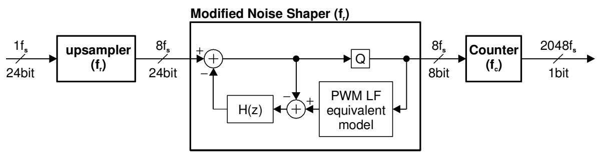

Figure 3: Low-frequency error model included into the noise shaper loop

In this way, the noise shaper "knows" what the spectral content produced by the PWM stage will be and thus apply its NTF to the correct variable. Doing this is less trivial than it seems. Depending on the signal, the PWM