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Phase Dithered Modulation in Switched Mode Excitation for Improved Amplitude Control

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***Abstract*—Multi-level switched mode transmitters provide a simplified method of exciting ultrasound transducers compared to linear amplifiers. Excitation waveforms are created which switch between typically 3 or 5 high voltage supplies with high drive current. Previously, Harmonic Reduction Pulse Width Modulation (HRPWM) has shown how control of amplitude and instantaneous frequency or phase can be achieved. Arbitrary excitation can be achieved using Arbitrary Harmonic Reduction Pulse Width Modulation (AHRPWM). However, the synthesis of exact tones frequencies remains problematic, especially where high frequencies, low amplitudes, or integer divisions of the transmitter sampling frequency occur. This paper presents a method of improving the amplitude control of modulated waveforms through the application of phase dithering. The addition of random noise to phase during the calculation of the modulated waveforms has the benefit of disturbing periodicity which occurs where the synthesized frequency is an integer division of the sampling frequency. An experimental investigation demonstrates the improvement of amplitude control from 11% to 3% standard deviation for a 10 MHz switched waveform sampled at 80 MHz.**

I. Introduction

Excitation of ultrasound transducers may be achieved using a range of methodologies including, from low to high complexity: negative impulses, multi-level switched excitation and analog power amplifiers. The use of switched excitation is especially pertinent where large numbers of channels are required for use with array transducers where the cost and size per channel may be constrained. Switched circuits are able to efficiently excite transducers with high voltage and high currents. Multi-level switched excitation waveform design techniques have been developed for the control of amplitude [1], [2] with harmonic control techniques [3], [4], [5], [6] and for sub-sample timing resolution for improved electronic focusing accuracy [7], thus allowing performance similar to power amplifiers.

Switched excitation schemes have been shown to allow precise excitation control in advanced ultrasound applications such as subharmonic imaging [8]guided waves [9], manipulation of microbubbles [10], and High Intensity Focused Ultrasound (HIFU) [11].

II. Phase Dithered Modulation

When a switched excitation waveform is designed, an algorithm calculates the waveform based on a series of parameters or an input analog waveform, generating a switched waveform with a number of discrete voltage levels sampled at rate according to the target ultrasound system. As the desired output frequency increases towards the sample rate, the number of samples per waveform cycle, and hence number of possible waveform designs becomes limited. This is especially problematic for frequencies which are an integer division of the sampling frequency as each cycle of the waveform becomes identical.

Figure 1 (top) demonstrates the synthesis of an analog tone (black) with an ideal 5-level switched waveform (blue). The HRPWM algorithm generates a switched waveform whereby the amplitude of the fundamental frequency equals that of the source analog waveform. The energy within the square edges are contained within the fifth or higher harmonics which are generally outside the bandwidth of the transducer and so filtered away.

When these switched waveforms are transferred to hardware, they must be sampled at a present frequency which has the effect of reducing the time resolution. As shown in figure 1 (middle) the resulting sampled HRPWM waveform differs from the ideal waveform. The precise transition times between voltages are lost in the sampling process. Additionally, when the target amplitude is varied, the algorithm may produce an identical waveform without any resulting change in amplitude.

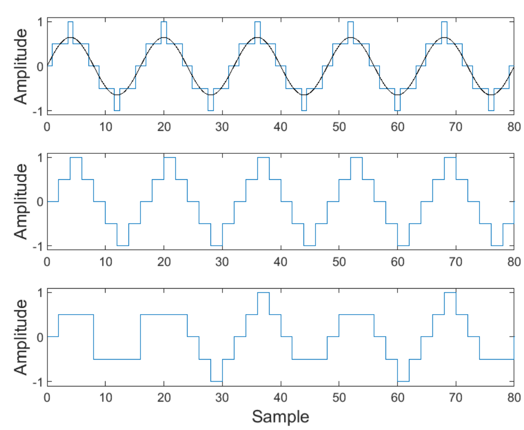

Fig. 1. Ideal HRPWM switched waveform synthesis (top, blue) of an analog waveform (top, black), regularly sampled (middle) and phased dithered modulated waveform (bottom).

In the illustrated example, each cycle is exactly 16 samples, as such each cycle of the switched waveform is identical.

This paper proposes an adaption to the HRPWM generation algorithm whereby dithering is applied to the sampling process to disrupt any periodicity in the waveform with the aim of improving the amplitude control. Small variations are introduced into each cycle such that over multiple cycles they average out to produce the desired target amplitude. A random dithering is applied to the phase of the source waveform with a magnitude of up to half the maximum phase increment of the waveform.

In the illustrated example, each cycle is exactly 16 samples resulting in a phase increment of 22.5° per sample. As such a random phase dither of magnitude $\pm 11.25°$ is applied to each sample. Figure 1 (bottom) shows the resulting waveform whereby each cycle differs allowing the overall average amplitude to match more closely with the desired amplitude.

III. Experimental Results and Discussion

An experimental investigation was conducted to validate the proposed method of phase dithered modulation. A series of five-cycle HRPWM waveforms were generated with various central frequencies and amplitudes from 1% to 100% in 1% increments. Both regular sampled and phase dithered waveforms were generated with a sampling frequency of 80 MHz.

The test waveforms were uploaded to an Cyclone V Field Programmable Gate Array (FPGA) (Intel Corporation, formerly Altera) connected to an experimental Gallium-Nitride (GaN) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) based pulser capable of switching between five discrete switched voltage levels. The output of the pulser was connected to a 50 Ω power load. The five discrete voltage levels used were -40, -20, 0, 20 and 40 volts. An MSO-S 204A Oscilloscope (Keysight Technologies) was used to capture the output voltage waveforms from the pulser.

Figures 2 and 5 show the non dithered (blue) and dithered (red) voltage waveforms for a 10 MHz and 16 MHz tone respectively. These frequencies were chosen as they are integer divisions of the sampling frequency. The 10 MHz tone has 8 samples per cycle, and the 16 MHz tone is 5 samples per cycle. Examination shows that each cycle of the non-dithered (blue) waveforms are identical, whilst the application of phase dithering shows variances between each cycle (red). For illustration amplitudes of 40%, 60% and 80% are presented.

Figures 3 and 6 show the amplitude control possible using non-dithered and dithered modulation for 10 MHz and 16 MHz respectively. The upper plot shows amplitude of the fundamental frequency following Fast-Fourier Transform (FFT) analysis of the ideal drive waveforms. The lower plot shows the fundamental frequency of the experimentally measured excitation voltages, as such it includes the effects of the excitation circuitry. Non-dithered generation of both the 10 MHz and 16 MHz tones result in it being possible to design only four discrete amplitudes due to the limited sample rate. With the application of phase dithering a continuously variable amplitude can be generated as shown in red.

Figures 4 and 7 show the error between the target amplitude and the actual amplitude. At 10 MHz the non-dithered amplitude error is -16% to +28% (standard deviation 11.6%) whilst for the phase dithered waveforms the error is reduced to -2% to +4% (std. dev. 3.2%). At 16 MHz the non-dithered amplitude error is -16% to +17% (std. dev. 8.2%) whilst for the phase dithered waveforms the error is reduced to -12% to +12% (std. dev. 4.4%).

IV. Conclusions

This paper has presented a method for improving the accuracy of amplitude control for switched excitation waveforms through the application of dithering to the phase of the modulating waveform. The proposed method is of particular applicability when a reduced integer number of samples represent a individual cycle of the excitation frequency. The proposed method has been experimentally validated and shown to reduce the error between the target amplitude and actual amplitude from 11.6% to 3.2% standard deviation.

Phase dithered modulation is of significance for high frequency applications where arbitrary control of excitation amplitude is necessary, for example aperture apodisation in array transducers, or where precise control of amplitude is required such as ultrasound therapy.

References

[1] D. Cowell and S. Freear, “Quinary excitation method for pulse compression ultrasound measurements,” *Ultrasonics*, vol. 48, no. 2, pp. 98 – 108, 2008.

[2] P. R. Smith, D. M. J. Cowell, and S. Freear, “Width-modulated square-wave pulses for ultrasound applications,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 60, no. 11, pp. 2244–2256, November 2013.

[3] D. M. J. Cowell, P. R. Smith, and S. Freear, “Phase-Inversion-based Selective Harmonic Elimination (PI-SHE) in multi-level switched-mode tone- and frequency- modulated excitation,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 60, no. 6, pp. 1084–1097, June 2013.

[4] D. Cowell, P. Smith, S. Harput, J. McLaughlan, and S. Freear, “Non-linear harmonic reduction pulse width modulation (HRPWM) for the arbitrary control of transducer-integrated switched excitation electronics,” in *2014 IEEE International Ultrasonics Symposium*, Sept 2014, pp. 807–810.

[5] D. M. J. Cowell, T. Carpenter, P. Smith, C. Adams, S. Harput, and S. Freear, “Performance of switched mode arbitrary excitation using harmonic reduction pulse width modulation (HRPWM) in array imaging applications,” in *2016 IEEE International Ultrasonics Symposium (IUS)*, Sept 2016, pp. 1–4.

[6] S. Freear, D. M. J. Cowell, and P. R. Smith, “Ultrasound generation,” United Kingdom Patent WO2 014 096 789A2, Dec. 19, 2012.

[7] P. R. Smith, D. M. J. Cowell, B. Raiton, C. V. Ky, and S. Freear, “Ultrasound array transmitter architecture with high timing resolution using embedded phase-locked loops,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 59, no. 1, pp. 40–49, January 2012.

[8] S. Harput, M. Arif, J. McLaughlan, D. M. J. Cowell, and S. Freear, “The effect of amplitude modulation on subharmonic imaging with chirp excitation,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 60, no. 12, pp. 2532–2544, Dec 2013.

[9] C. Adams, S. Harput, D. Cowell, T. M. Carpenter, D. M. Charutz, and S. Freear, “An adaptive array excitation scheme for the unidirectional enhancement of guided waves,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 64, no. 2, pp. 441–451, Feb 2017.

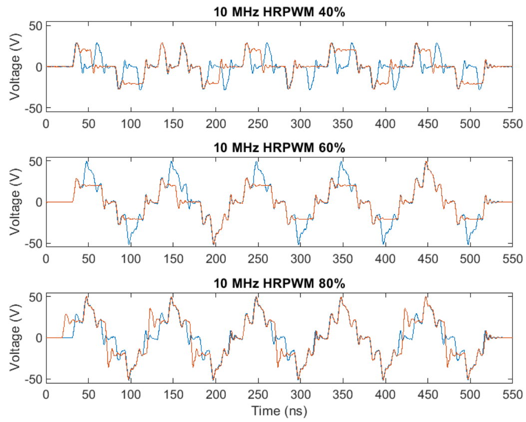

Fig. 2. Experimental non-dithered (blue) and phased dithered (red) waveforms for 40%, 60% and 80% amplitudes at 10 MHz.

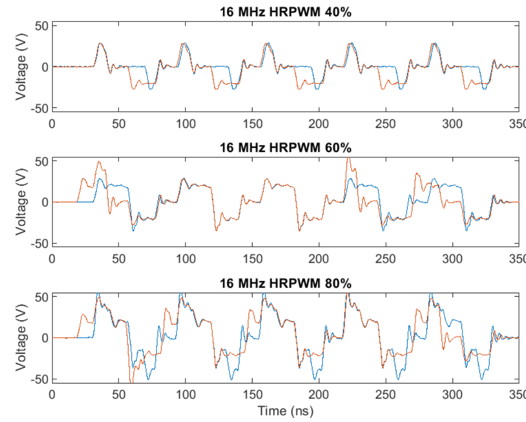

Fig. 5. Experimental non-dithered (blue) and phased dithered (red) waveforms for 40%, 60% and 80% amplitudes at 16 MHz.

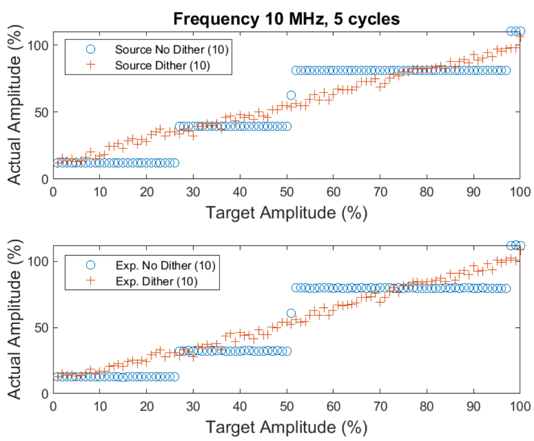

Fig. 3. Amplitudes of the fundamental frequency at 10 MHz for non-dithered (blue) and phased dithered (red), for ideal (top) and experimental (bottom) waveforms.

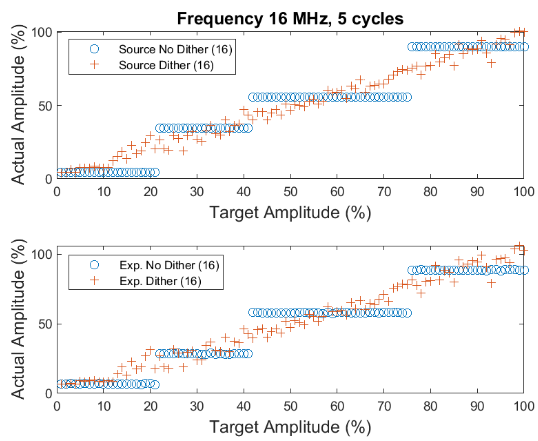

Fig. 6. Amplitudes of the fundamental frequency at 16 MHz for non-dithered (blue) and phased dithered (red), for ideal (top) and experimental (bottom) waveforms.

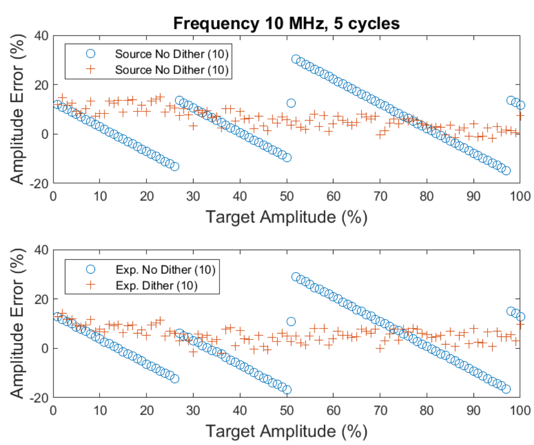

Fig. 4. Amplitude error of the fundamental frequency at 10 MHz for non-dithered (blue) and phased dithered (red), for ideal (top) and experimental (bottom) waveforms.

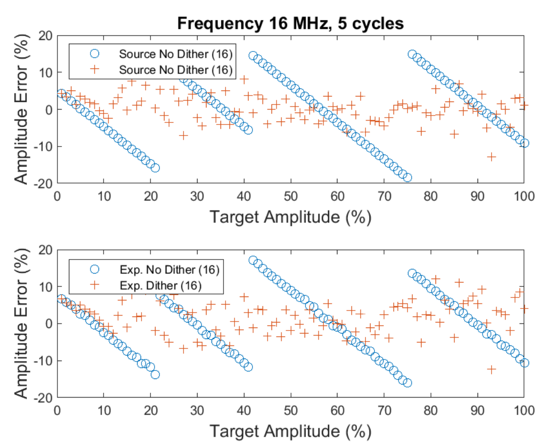

Fig. 7. Amplitude error of the fundamental frequency at 16 MHz for non-dithered (blue) and phased dithered (red), for ideal (top) and experimental (bottom) waveforms.

[10] L. Nie, S. Harput, D. M. J. Cowell, T. M. Carpenter, J. R. Mclaughlan, and S. Freear, "Combining acoustic trapping with plane wave imaging for localized microbubble accumulation in large vessels," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, no. 7, pp. 1193–1204, July 2018.

[11] C. Adams, T. M. Carpenter, D. Cowell, S. Freear, and J. R. McLaughlan, "Hifu drive system miniaturization using harmonic reduced pulsewidth modulation," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, no. 12, pp. 2407–2417, Dec 2018.