Proceedings Paper:

Cowell, DMJ orcid.org/0000-0003-0854-542X, Harput, S orcid.org/0000-0003-0491-4064 and Freear, S orcid.org/0000-0001-7858-4155 (2015) Arbitrary waveform generation based on phase and amplitude synthesis for switched mode excitation of ultrasound imaging arrays. In: Proceedings. 2015 IEEE International Ultrasonics Symposium (IUS), 21-24 Oct 2015, Taipei, Taiwan. IEEE . ISBN 978-1-4799-8182-3

https://doi.org/10.1109/ULTSYM.2015.0280

Arbitrary Waveform Generation based on Phase and Amplitude Synthesis for Switched Mode Excitation of Ultrasound Imaging Arrays

D. M. J. Cowell, S. Harput, and S. Freear

School of Electronic and Electrical Engineering, University of Leeds, Leeds UK.
E-mail: d.m.j.cowell@leeds.ac.uk

***Abstract*—The implementation of miniaturised excitation circuitry in portable systems and transducer integrated front ends is challenging due to the requirements for high voltage and high current generation. Arbitrary excitation performed using digital to analog converters and high specification amplifiers cannot be easily miniaturised. Switched excitation circuitry can easily miniaturised but requires careful waveform design to achieve arbitrary excitation. Previously, Harmonic Reduction Pulse Width Modulation (HRPWM) has been proposed to allow the design of low harmonic content switched mode excitation signals through a parameterized design process. This paper proposes the technique arbitrary-HRPWM (AHRPWM) to allow the synthesis of three and five level true arbitrary switched mode excitation waveforms. The technique is demonstrated through the design and evaluation of linear frequency modulated waveforms that have been predistorted to compensate for transducer characteristics. After simulating the transducers response the resulting switched mode waveforms show am 0.06% amplitude error in the time domain compared to the amplified analog waveform and -45 dB and -35 dB third harmonic powers for the three and five level switched mode waveforms respectively.**

I. INTRODUCTION

With advances in transducer and electronics design, integration of transmit and receive circuitry directly into the probe head is becoming a reality thus overcoming restrictions of transducer cabling [1]–[5]. It is possible to integrate a miniaturized, high current, high voltage, high efficiency switched excitation circuits [6]–[8] into the transducer [5]. The ultrasound system design typically requires arbitrary control of the excitation waveform: amplitude control for temporal windowing and spatial array apodisation, frequency and phase control for coded excitation and minimal harmonics for harmonic [9] and superharmonic imaging [10].

Harmonic Reduction Pulse Width Modulation (HRPWM) has been previously demonstrated for the design of five level switched mode excitation waveforms with suppressed third and even numbered harmonics [11], [12]. HRPWM required a parameterized design of a phase modulating waveform and waveform envelope as input parameters. This approach to waveform design is well suited to situations where the waveform has limited customisation and can be easily represented arithmetically. Parametrised waveform design is not suitable where a waveform has true arbitrary characteristics, for example where the waveform is optimised to transducer or system properties through algorithmic design or by deconvolution with transducer impulse responses.

This paper presents a extended arbitrary-HRPWM (AHRPWM) method to support true arbitrary waveform design by removing the necessity for parameterized waveform inputs. The proposed method only requires the desired waveform, sampling frequency and switching voltages as inputs. Additionally, the AHRPWM method is demonstrated in both three and five switching voltage modes. The three level mode is especially suited to portable systems and transducer integrated excitation where reduced circuit complexity is required.

II. METHODOLOGY

The process of synthesising an analog excitation waveform using a switched mode excitation waveform using AHRPWM can be described in four distinct process: window recovery, phase recovery, modulation carrier generation and switched waveform generation, as illustrated in figure 1.

A. Envelope Recovery

The first stage of AHRPWM is to generate the input waveforms outermost envelope. This may be achieved using the analytic representation of the input signal. The real signal may be transformed into an analytic signal using the Hilbert transform. An analytic signal has no negative frequency components, however is expressed in complex notation rather. The envelope is the absolute value of the complex valued analytic signal.

B. Phase Recovery

The second stage of AHRPWM is to generate the instantaneous phase of the input waveform. The instantaneous phase of the input signal is the argument of the complex valued analytic signal.

C. Modulation Carrier Generation

The third stage of AHRPWM is to generate modulation carrier waveforms. The instantaneous phase of the input signal is used to create a series of modulation carriers each representing the individual switched excitation voltage levels. Each modulation carrier waveform is designed such that the power

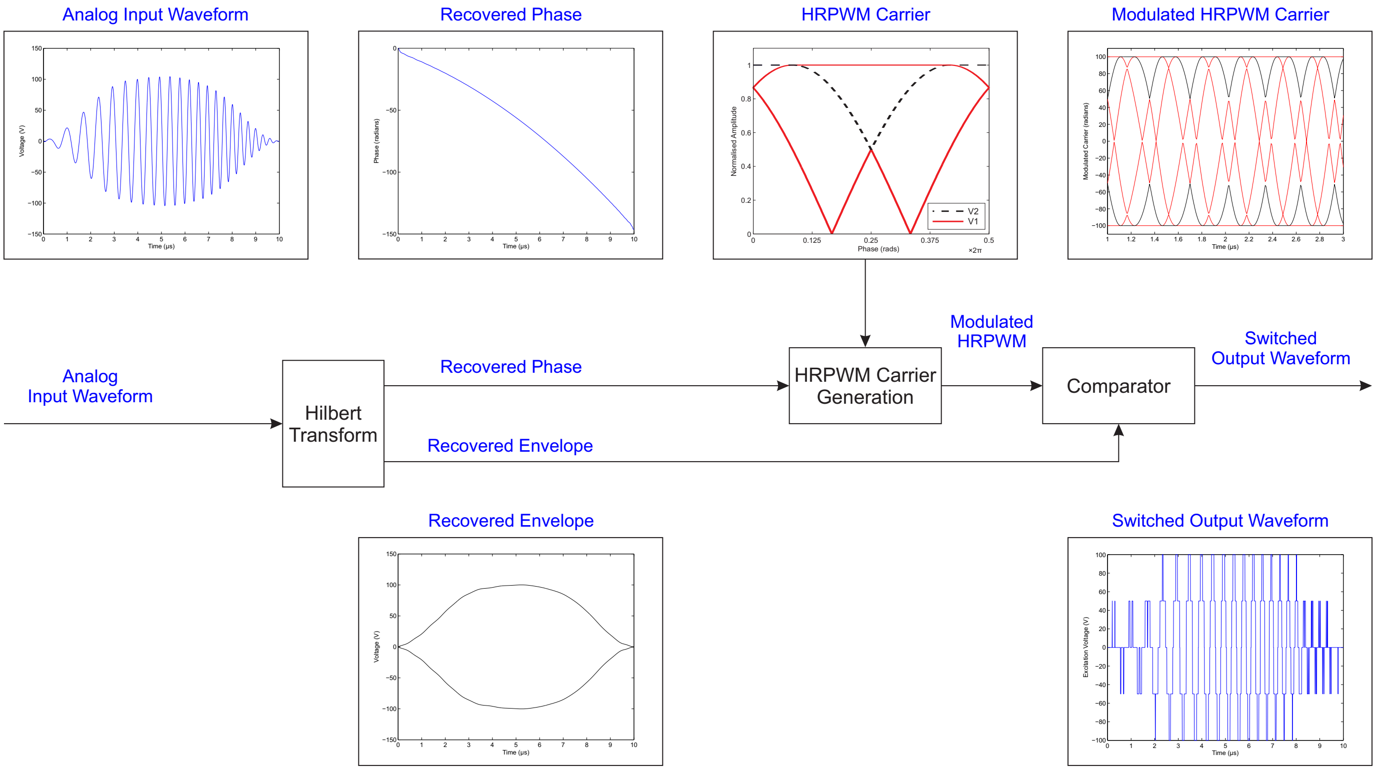

Fig. 1. Flow-diagram illustrating the process of synthesising an arbitrary analog excitation waveform as a five level switched mode excitation waveform using Arbitrary Harmonic Reduction Pulse Width Modulation (AHRPWM).

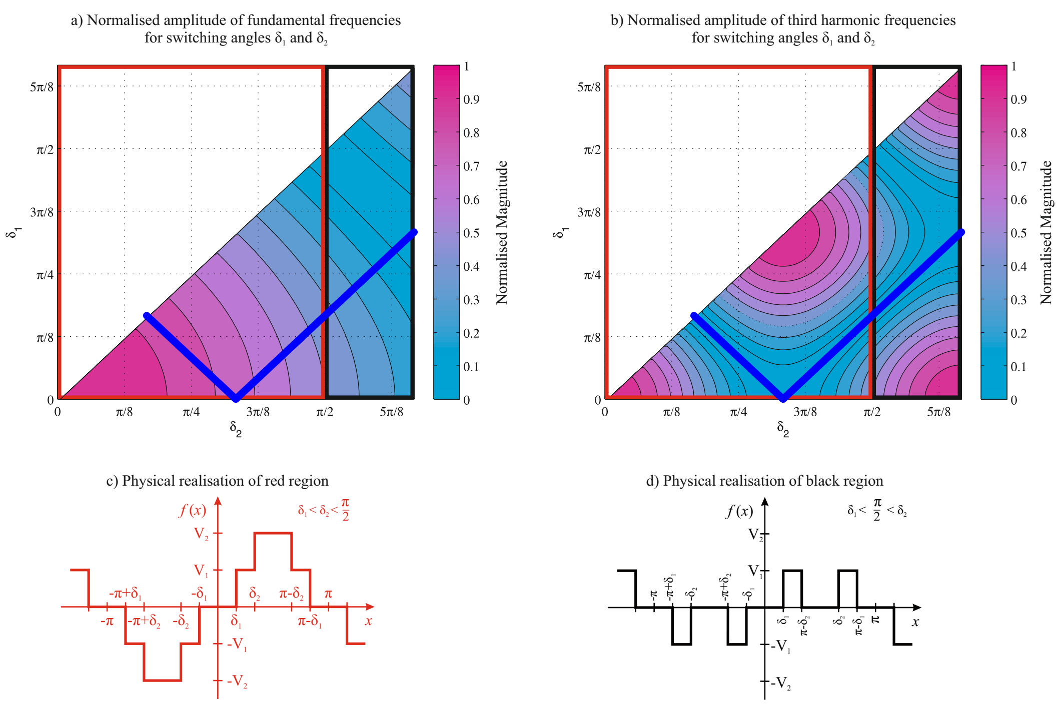

Fig. 2. Illustration of fundamental (a) and third harmonic (b) content of a AHRPWM waveform for varying switching angles δ_1 and δ_2 and the time domain realisation of HRPWM waveforms (c and d).

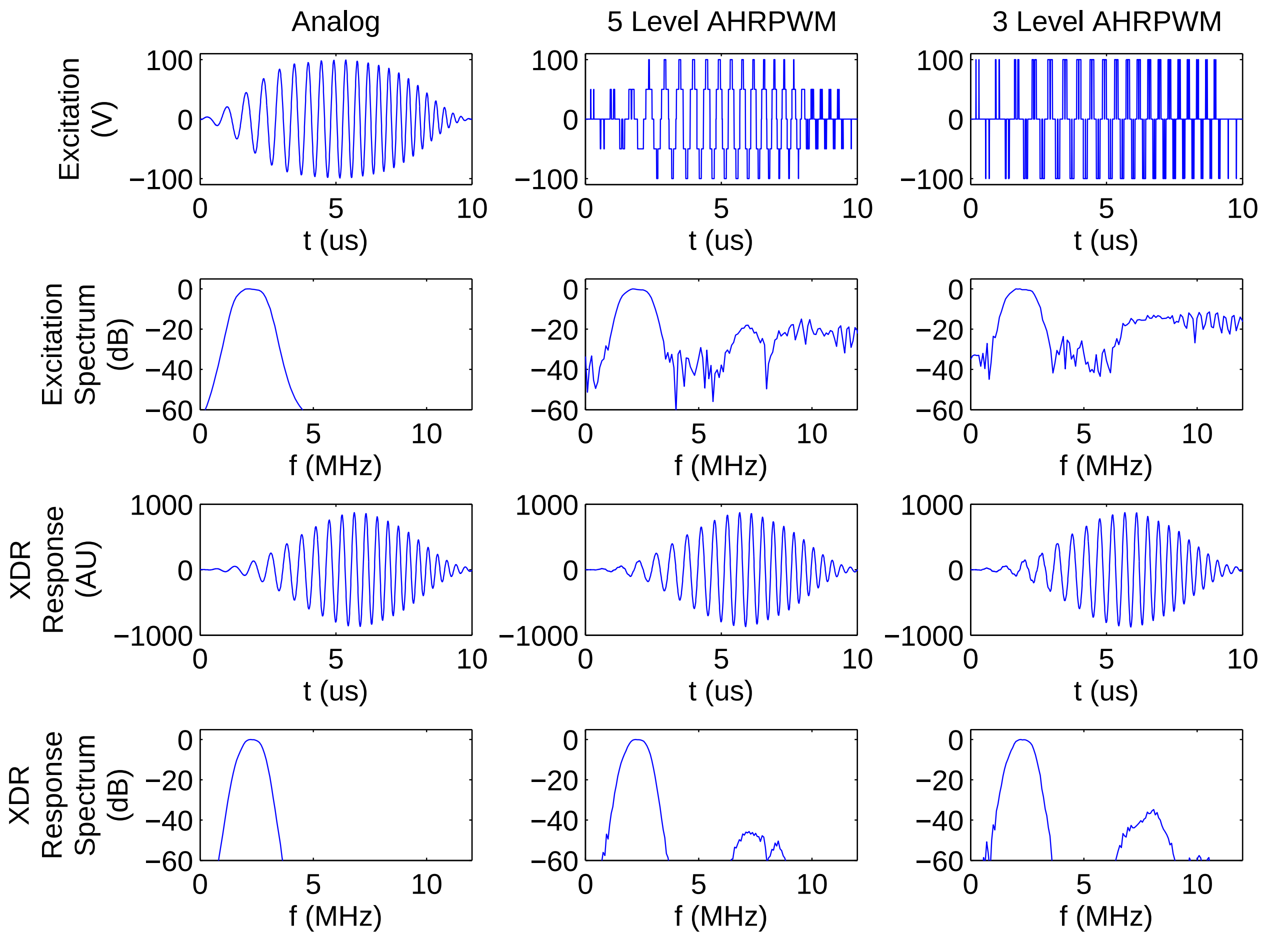

Fig. 3. Illustration of the proposed AHRPWM technique for the synthesis of an arbitrary input chirp waveform pre-distorted to compensate for transducer characteristics showing excitation and transducer response waveforms and spectra for analog, five level AHRPWM and three level AHRPWM excitation.

contained in the fundamental frequency is linearised against amplitude and the third harmonic is mathematically suppressed [12]. The modulation carrier now defines the time-frequency relationship of the output waveform.

D. Switched Waveform Generation

The fourth and final stage of the AHRPWM is to generate the switched excitation waveforms. Each modulation carrier waveform is compared with the signal envelope recovered in stage one. The intersection of the envelope with each modulation carrier defines the width of each output pulse for switching voltage level.

A symmetrical quinary (five level) switched mode waveform consists of voltage levels $\pm V$, $\pm V/2$ and GND (0V). HRPWM defines two switching angles δ_1, δ_2 that control the spectral properties of the switched waveforms. There exist two distinct characteristic switched waveforms each defined by the value of δ_1, δ_2. The power contained in the fundamental and third harmonic are represented in figure 2 as a $\delta_1 - \delta_2$ plane.

The first region is defined by $\delta_1 < \frac{\pi}{2} < \delta_2$ and is realised as two positive and two negative pulses at $\pm V/2$ and realises cycles of the output waveform where the output amplitude is less than half the maximum switching voltage. The second region is defined by $\delta_1 < \delta_2 < \frac{\pi}{2}$ and is realised as a positive and negative stepped waveform containing $\pm V$, $\pm V/2$ and GND (0V) and realises cycles of the output waveform where the output amplitude is greater than half the maximum switching voltage.

Typically a real excitation signal contains pulses from both regions depending on the envelope profile. Given an excitation system with three voltage levels, or where only three levels are desired, it is possible to restrict the number of voltage levels used in the switched waveform by limiting the maximum envelope amplitude to less than half the maximum voltage level. Limiting the output waveform to three levels reduces the amplitude accuracy of the output waveform for a given switching sampling frequency compared to five level excitation.

III. Results and Discussion

The effectiveness of the proposed AHRPWM method in both five and three level mode has been investigated for an arbitrary analog input signal. The required voltage to generate 100 kPa peak negative pressure at 20 mm from a 2.25 MHz, 0.25 inch diameter, immersion transducer (Olympus NDT V323) to tone excitation using an arbitrary waveform generator (AWG) and class A amplifier (E&I A300) was measured using at various frequencies from 1.6 to 2.8 MHz was measured using a 0.2 mm diameter needle hydrophone (Precision Acoustics Ltd). The resulting data was used to pre-distort a Hann windowed chip with central frequency 2.25 MHz and 100% fractional bandwidth, to increase the 20 dB bandwidth from 1.9 MHz to 2.3 MHz as shown in figure 3 (left). The resulting time domain waveform was used as an input to the AHRPWM algorithm to generate five (figure 3 (middle) and three (figure 3 (right) level switched waveforms sampled at 160-MHz. The spectra of each excitation signal is shown in the second row of figure 3. The corresponding transducer response to each excitation waveform and the associated spectra is shown in the third and fourth row of figure 3.

Spectra analysis of the AHRPWM switched excitation waveforms show a maximum third harmonic of -18 dB for the five level and -14.6 dB for the three level waveforms. After convolving the excitation waveform with the impulse response of the transducer a deviation of 0.06% in simulated output pressure is observed. The spectra of the simulated transducer responses shows a maximum third harmonic of -45 dB for the five level and -35 dB of the three level switched excitation waveforms.

IV. Conclusions

This paper has proposed an extension to the HRPWM algorithm to allow the synthesis of arbitrary analog excitation waveforms using three or five level switched excitation. The AHRPWM removes the necessity for parameterized waveform design by internally calculating the envelope and instantaneous phase of the input excitation signal. This method has the potential to allow true arbitrary excitation using multi-level switched mode excitation with accurate amplitude and phase control and minimised third harmonic, and will be especially applicable to miniaturised ultrasound circuitry embedded into the transducer and for portable ultrasound systems.

References

[1] G. Athanasopoulos, S. Carey, and J. Hatfield, "Circuit design and simulation of a transmit beamforming ASIC for high-frequency ultrasonic imaging systems," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 58, no. 7, pp. 1320–1331, July 2011.

[2] Z. Yu, S. Blaak, Z. yao Chang, J. Yao, J. Bosch, C. Prins, C. Lancée, N. de Jong, M. Pertijs, and G. Meijer, "Front-end receiver electronics for a matrix transducer for 3-D transesophageal echocardiography," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 59, no. 7, pp. 1500–1512, July 2012.

[3] G. Gurun, C. Tekes, J. Zahorian, T. Xu, S. Satir, M. Karaman, J. Hasler, and F. Degertekin, "Single-chip CMUT-on-CMOS front-end system for real-time volumetric IVUS and ICE imaging," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 61, no. 2, pp. 239–250, February 2014.

[4] T. Christiansen, M. Rasmussen, J. Bagge, L. Nordahl Moesner, J. Jensen, and E. Thomsen, "3-D imaging using row–column-addressed arrays with integrated apodization– part ii: transducer fabrication and experimental results," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 62, no. 5, pp. 959–971, May 2015.

[5] C. Tekes, T. Xu, T. M. Carpenter, S. Bette, U. Schnakenberg, D. Cowell, S. Freear, O. Kocaturk, R. J. Lederman, and F. L. Degertekin, "Real-time imaging system using a 12-MHz forward-looking catheter with single chip CMUT-on-CMOS array," in *Ultrasonics Symposium (IUS), 2015 IEEE International*, October 2015.

[6] C.-C. Huang, P.-Y. Lee, P.-Y. Chen, and T.-Y. Liu, "Design and implementation of a smartphone-based portable ultrasound pulsed-wave doppler device for blood flow measurement," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 59, no. 1, pp. 182–188, January 2012.

[7] G. duck Kim, C. Yoon, S.-B. Kye, Y. Lee, J. Kang, Y. Yoo, and T.-K. Song, "A single FPGA-based portable ultrasound imaging system for point-of-care applications," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 59, no. 7, pp. 1386–1394, July 2012.

[8] W. Qiu, Y. Yu, F. K. Tsang, and L. Sun, "A multifunctional, reconfigurable pulse generator for high-frequency ultrasound imaging," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 59, no. 7, pp. 1558–1567, July 2012.

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

[10] S. Harput, J. McLaughlan, D. Cowell, and S. Freear, "Superharmonic imaging with chirp coded excitation: filtering spectrally overlapped harmonics," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 61, no. 11, pp. 1802–1814, November 2014.

[11] D. Cowell, P. Smith, and S. Freear, "Phase-inversion-based selective harmonic elimination (PI-SHE) in multi-level switched-mode tone- and frequency- modulated excitation," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, vol. 60, no. 6, pp. 1084–1097, June 2013.

[12] 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 *Ultrasonics Symposium (IUS), 2014 IEEE International*, Sept 2014, pp. 807–810.