Performance of Switched Mode Arbitrary Excitation using Harmonic Reduction Pulse Width Modulation (HRPWM) in Array Imaging Applications

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Abstract—Switched excitation allows the miniaturisation of excitation circuitry for transducer integrated front ends, high channel count and portable ultrasound systems. Harmonic Reduction Pulse Width Modulation (HRPWM) provides a method to design five level switched mode excitation signals with control of instantaneous amplitude, frequency and phase plus minimised third harmonics for advanced ultrasound applications. This paper details the application of HRPWM using commercial transmit front end integrated circuits and linear array transducers. The ability of HRPWM to control the pressure of the ultrasound wave is investigated. A full scale error between desired and measured pressure of 3.5% at 4.1 MHz is demonstrated. The temporal windowing of linear frequency modulated excitation signals using HRPWM is demonstrated. Pulse compression linear imaging of a tissue phantom is demonstrated where an improvement in the -20 dB axial resolution of a nylon mono-filament target from 2.14 mm using bipolar excitation to 1.88 mm using HRPWM is shown.

I. Introduction

Circuit miniaturisation allows integration of the ultrasound front end directly into the probe head as a means to overcoming limitations imposed by cabling in multi-channel imaging systems [1]–[4]. The transmit front end can be miniaturised and a high current, high voltage, high efficiency switched mode excitation [1], [5], [6] can be fabricated into the transducer [4]. Ultrasound systems require excitation amplitude control to adjust acoustic pressure, waveform shaping (temporal) and array apodisation (spatial), frequency control for coded excitation and reduced excitation harmonics for harmonic imaging. Control of excitation parameters allows the development of methods such as transmit pre-distortion [7], subharmonic imaging [8], superharmonic imaging [9] and microbubble manipulation [10].

This paper explores the application of Harmonic Reduction Pulse Width Modulation (HRPWM) [11]–[13] switched excitation using commercial transmit front end integrated circuits (ICs) for the control of ultrasound transmit waveforms with width bandwidth linear array transducers. The linearity of the desired HRPWM amplitude and pressure of the ultrasonic wave is ascertained through hydrophone measurements and HRPWM demonstrated for the temporal windowing of linear frequency modulated (LFM) excitation signals. Finally, HPRPWM for apodization and windowing of LFM signals in pulse compression linear imaging is demonstrated.

II. Harmonic Reduction Pulse Width Modulation (HRPWM)

Analog and switched (or pulsed) ultrasound excitation waveforms vary in their fundamental mode of operation. In analog excitation the instantaneous excitation voltage is continuously varied with time. Both instantaneous amplitude and frequency are directly encoded in the excitation signal. In switched excitation the instantaneous voltage is switched between a reduced number of discrete levels. Amplitude and frequency are encoded by varying the temporal position and duration of a series of pulses or voltage transitions. Switched excitation typically relies on the transducer possessing bandpass frequency characteristics and as such filters undesired harmonics.

The HRPWM technique allows that control of excitation amplitude, and hence ultrasonic wave pressure, by defining two waveforms with varying switching angles δ_1 and δ_2 as illustrated in figures 1a and 1b [11], [12]. The amplitude of the fundamental and harmonics are controlled by adjusting modulation carrier waveforms. The white path indicated in figure 1c allows fundamental amplitude to be continuously varied and the third harmonic suppressed. An arbitrary waveform can be synthesised by performing amplitude and phase analysis using the AHRPWM process [13].

III. Materials and Methods

The aim of this work is to demonstrate the use of HRPWM for excitation waveform control using a commercial switched mode excitation front-end chip set.

A. Ultrasound Array Research Platform II (UARP II)

The University of Leeds has developed the Ultrasound Array Research Platform II (UARP II) as a tool for the development of novel ultrasound techniques. The UARP II is constructed using multiple modules each providing sixteen channels of transmit and receive functionality. Each module is based around an Altera Stratix V FPGA that is connected to a host computer using eight lanes of third generation PCI Express (PCIe). Each module is synchronised to a low jitter global 160 MHz clock and trigger signal that is distributed between each module. The UARP II is configured using Matlab which interfaces to custom software libraries and drivers.

a) Physical realisation of red region $\delta_2 \leq \frac{\pi}{2}$

$f(x)$

V_2, V_1, $-V_1$, $-V_2$

$-\pi+\delta_1$, $-\delta_1$, δ_2, $\pi-\delta_2$, π

$-\pi$, $-\pi+\delta_2$, $-\delta_2$, δ_1, $\pi-\delta_1$, x

b) Physical realisation of black region $\delta_2 > \frac{\pi}{2}$

$f(x)$

V_2, V_1, $-V_1$, $-V_2$

$-\pi$, $-\pi+\delta_1$, $-\delta_2$, $-\pi+\delta_2$, $-\delta_1$

δ_1, $\pi-\delta_2$, δ_2, $\pi-\delta_1$, π, x

c) Normalised amplitude of fundamental, 3rd and 5th harmonics in 5 level switched excitation for switching angles δ_1 and δ_2

f_0

$3f_0$

$5f_0$

δ_1 (deg), δ_2 (deg)
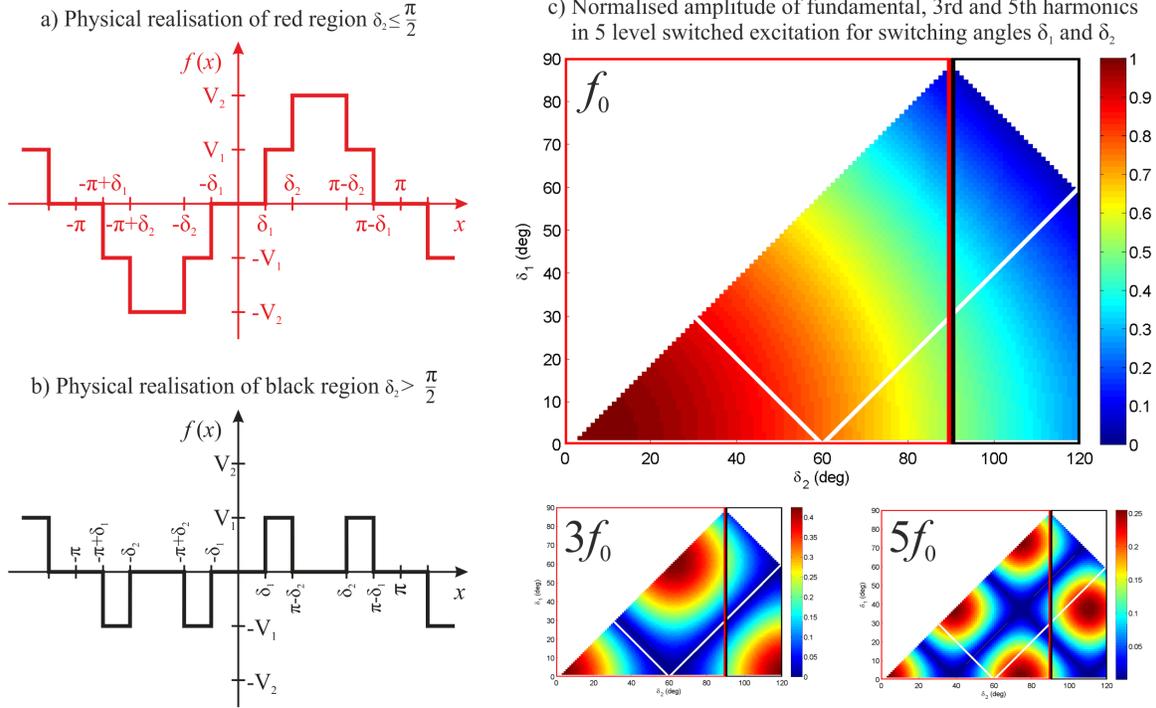
Fig. 1. Illustration of HPRPWM switched waveforms where (a) $\delta_2 \leq 90$ and (b) $\delta_2 > 90$, and (c) fundamental, third and fifth harmonic content of a HRPWM waveform for varying switching angles δ_1 and δ_2 where $V_2 = 2V_1$.

The transmit stage is based around four MAX14808 integrated circuits (ICs) each providing four channel of five level excitation up to ± 100 volts at 2 amps. Each transmitter is operated in a synchronous mode whereby the digital excitation control signals are gated by a phase matched 160 MHz clock signal to reduce both jitter in the excitation signal timing and channel to channel timing jitter. In addition, the MAX14808 IC provides integrated transmit-receive switch functionality. The transmit stage is powered by a four channel Keysight N6700B programmable power supply unit configured with two 100 V, 100 W modules and two 50 V, 100 W autoranging modules, configured to supply positive and negative voltages. This configuration allows the individual control of all four non-ground excitation voltages, based on the required experimental parameters.

The receive stage is based around two AFE5808 integrated analog front end (AFE) ICs from Texas Instruments. Each AFE5808 IC provides eight channels consisting of low noise amplifier (LNA), variable gain attenuator (VGA), programmable gain amplifier (PGA), low pass filter (LPF), and an analog to digital converter (ADC). The high speed digital output from the AFE is sampled by the FPGA into a zero bottleneck receive data path into on-board memory contained in each module.

B. Transducer

The UARP II features interchangeable transducer connections allowing operation with any transducer of know pinout.

During this investigation a 128 element linear array transducer, L3-8/40EP (Prosonic Co. Ltd., Taiwan) with an operating frequency range of 3 to 8 MHz and an element pitch of 0.3048 mm was used.

C. Hydrophone Pressure Measurement

Acoustic measurements were performed using a calibrated differential membrane hydrophone (Precision Acoustics Ltd., UK) with 0.4 mm active element size, and sensitivity of 339 mV/MPa sensitivity with ± 2 dB frequency response in the range 1 to 30 MHz. The output of the membrane hydrophone is sampled using a MSO104a mixed signal digital storage oscilloscope (Keysight Instruments, USA) with 10 bit resolution, 1 GHz bandwidth and 20 GSPS sampling. The MSO104a is configured with segmented memory such that each output trigger from the UARP II corresponding to a transmit event can be captured in real time. This allows the rapid hydrophone measurement of complex operating sequences. Additionally, the MSO104a was configured to capture each sequence 64 times to allow for waveform averaging during post processing.

The transducer and membrane hydrophone were both mounted on three axis micrometer positioning stages in degassed, filtered and deionised water in a tank lined with Aptflex F28 acoustic absorbing material.

IV. RESULTS AND DISCUSSION

A. Excitation Amplitude Linearity

The primary aim of HRPWM is to achieve control of the amplitude of an ultrasound wave through the modulation of a switched mode excitation signal. As such it is desirable to compare the linearity of the desired output amplitude to measured ultrasound waveform pressure.

The L3-8/40EP linear array transducer and membrane hydrophone were assembled with a separation of 30 mm. The transducer and hydrophone were aligned such that the positive to negative pressure was maximised for the 64th element. The UARP II was configured to systematically excite element 64 with a 10 cycle tone burst of frequency 4.1 MHz. HRPWM waveforms were calculated in single degree increments of δ_2 as shown by the white trace in 1a providing coverage of the complete HRPWM amplitude range. The excitation voltage levels were set to ± 25 volts, ± 12.5 volts and ground (0 volts), to reduce the effect of non-linear wave propagation in the hydrophone test tank. Figure 2 shows the relationship between the normalised excitation amplitude and the normalised spectral energy amplitude of the hydrophone measured pressure. A maximum $\pm 3.5\%$ full scale error was measured as indicated.

B. Time Windowing of Excitation Waveforms

The ability of HRPWM to dynamically control transmit amplitude is of great significance for use in array based ultrasound imaging where temporal windowing of the excitation signal and lateral apodization of the imaging aperture both provide performance gains.

A linear frequency modulated waveform with a central frequency of 5 MHz, bandwidth of 2 MHz, duration of 2 μs and temporal Hann windowing was generated using HRPWM. For comparison, a two level, bipolar waveform with the same parameters except rectangular windowing was created. Both excitation waveform were uploaded to the UARP II imaging system and the resulting ultrasound waves characterised using
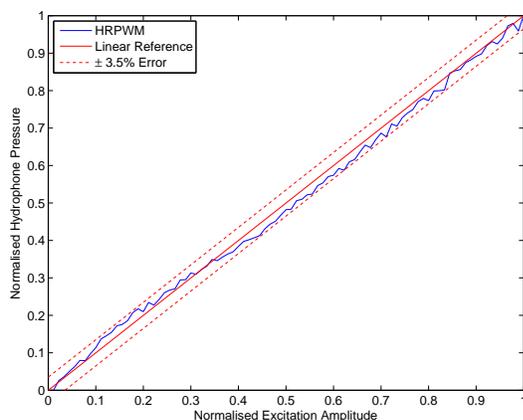
the same experimental configuration of linear array transducer and hydrophone as previously described. The resulting hydrophone measured pressure is for both bipolar and HRPWM encoded waveforms is shown in figure 3 where the ability of HRPWM to control excitation amplitude is demonstrated. Both bipolar and HRPWM waveforms were designed with identical phase. As such the zero phase offset between the two measured pressure waves indicates that the HRPWM process does not introduced any undue phase shift.

C. Tissue Phantom Imaging

The effect of HRPWM on tissue imaging using a linear array transducer has been evaluated using a CIRS Model 040GSE, multi-purpose, multi-tissue phantom. The CIRS phantom contains a group of 100μm diameter nylon monofilaments arranged at depths of 10 to 160 mm in 10 mm steps in a scattering backgrounds with 0.5 dB/cm-MHz attenuating. These filaments have been selected as imaging targets. A Hann window apodized linear aperture of 16 elements was created with 16 individual LFM, Hann windowed, 4 to 6 MHz frequency, 2μs duration signals. Focusing was configured at 20 mm in both transmit and receive modes. The linear imaging transducer was fixed in position above the CIRS phantom and imaging with bipolar and HRPWM excitation waveforms was performed. Delay and sum beamforming was preformed followed by matched filtering of the each image line.

The post beamformed waveforms in figure 4a and 4b show the echo from the nylon monofilament at 20 mm depth and the effect of HRPWM amplitude control on the raw A-lines. Following matched filter pulse compression, the axial resolution, figure 4c, shows an improvement in the -20 dB axial resolution from 2.14 to 1.88 mm through the use of HRPWM compared to bipolar excitation through the suppression of near sidelobes. The resulting B-mode images for bipolar and HRPWM imaging are shown in figures 4d and 4e respectively.

Fig. 2. Normalised pressure amplitude linearity of a single linear transducer element excited by a HRPWM 10 cycle 4.1 MHz tone, measured using a membrane hydrophone at 30 mm.
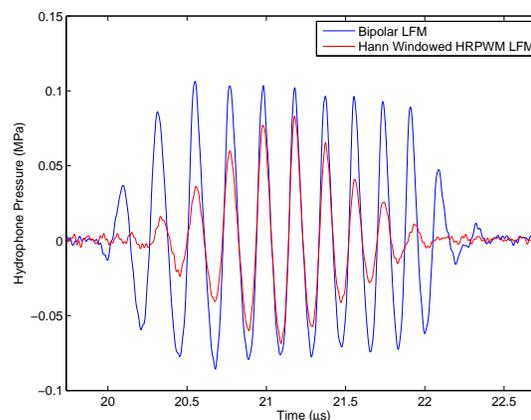
Fig. 3. Hydrophone pressure measurement of a single linear transducer element excited by a bipolar LFM and a Hann windowed HRPWM LFM waveform measured at 30 mm.
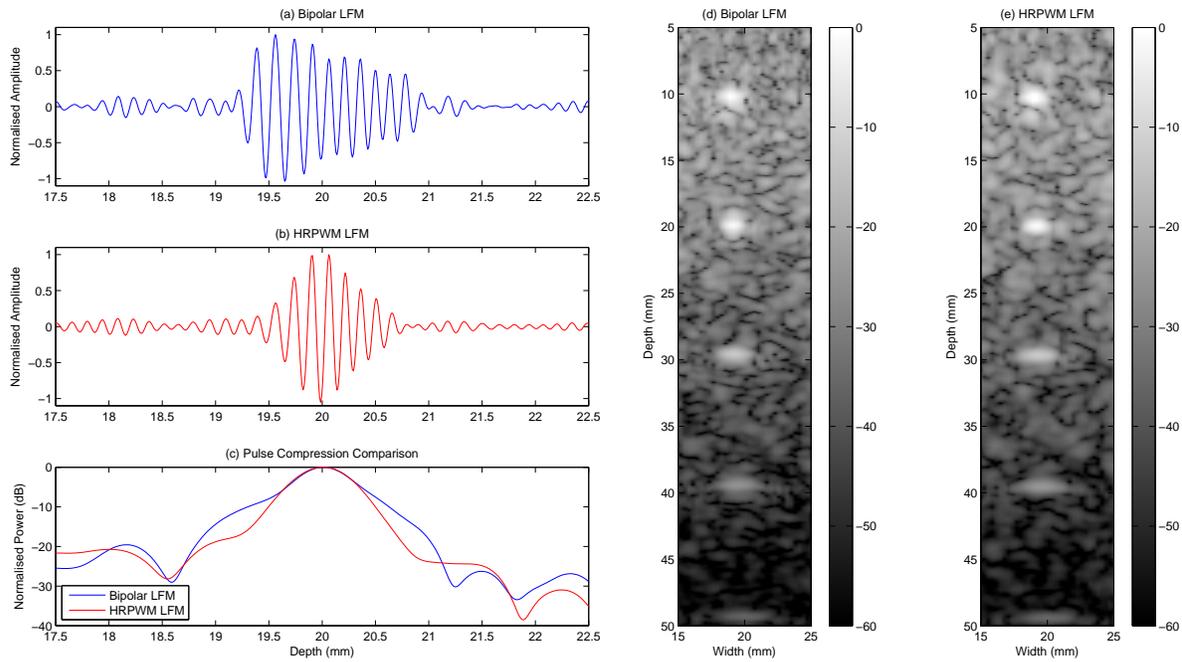
Fig. 4. Comparison of bipolar and HRPWM excitation in linear array imaging using a tissue mimicking phantom. Received beamformed echoes from a nylon monofilament at 20 mm depth for (a) bipolar and (b) HRPWM windowed and apodized excitation. Pulse compressed output (e) after beamforming and matched filtering. B-mode images using (d) bipolar and (e) HRPWM excitation.

V. CONCLUSIONS

This paper has demonstrated the ability of HRPWM to control transmit amplitude. This has been shown through membrane hydrophone measurements and amplitude linearity shown not to deviate by more than 3.5% for nominal 4.1 MHz transmission. LFM pulse compression linear imaging with windowing and apodization has been demonstrated using a tissue mimicking phantom and HRPWM has shown to improve the -20 dB resolution compared to bipolar excitation. HRPWM provides a practical and low-cost route to implementing arbitrary excitation using a commercial switched mode ultrasound transmitter front-end in an array imaging system.

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