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# Modified Harmonic Reduction Pulse Width Modulation (mHRPWM) for Switched Excitation of Resonant HIFU Transducers

David M. J. Cowell*, Thomas M. Carpenter, Christopher Adams, Steven Freear
Ultrasonics and Instrumentation Group, School of Electronic and Electrical Engineering,
University of Leeds, Leeds, LS2 9JT, UK
Email: *d.m.j.cowell@leeds.ac.uk

***Abstract*—High Intensity Focused Ultrasound (HIFU) is reliant on carefully designed excitation systems capable of high power, and low distortion. The use of array transducers additionally requires amplitude control for apodization and attenuation compensation plus phase control for inter element timing for beamstearing, focusing and correction. Power amplifiers possess all the required characteristics except they can be expensive and bulky thus placing barriers to adoption especially for large channel count arrays. Switched mode excitation systems are capable of fulfilling all requirements except minimizing distortion can be problematic due to the lack of availability of suitably high speed MOSFETs placing restrictions of waveform design. This work presents an modification to the Harmonic Reduction Pulse Width Modulation (HRPWM) method specifically designed to minimize harmonic distortion in systems constrained by MOSFET performance in HIFU excitation systems. The proposed method is of significance as the use of external filtering and transformer coupling of the excitation waveform is not required. The proposed method is demonstrated through experimental hydrophone testing with a 1.1 MHz HIFU transducer and demonstrates the successful generation of excitation waveforms with continuously variable amplitude control and low third harmonic output.**

## I. INTRODUCTION

High Intensity Focused Ultrasound (HIFU) is a non-invasive surgical technique with numerous therapeutic medical applications [1] [2] which is often performed with transducers connected to analog power amplifiers, selected due to their low harmonic distortion and high power handling capabilities. Large scale implementation requires the design of cost effective excitation electronics capable of driving multi-element arrays without sacrificing amplitude control or phase performance. Switched excitation schemes have been shown to allow precise excitation control in advanced ultrasound imaging applications [3]–[5]. Switched excitation waveform design techniques have been shown to minimize harmonics [6]–[8], however the high power and high voltage demands of switched excitation design for HIFU require the use of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) with non-ideal switching characteristics resulting in gaps in the excitation amplitudes achievable with minimized harmonics.

This paper presents a method of designing five level switched excitation waveforms with minimized third harmonics suitable for the excitation of HIFU transducers without the requirement for external filtering or transformer coupling of the excitation waveform.

## II. HIFUARP

The University of Leeds High Intensity Focused Ultrasound Array Research Platform (HIFUARP) is a 16-channel high-power ultrasound system for exciting HIFU transducers. The system consists of a set of modular 5-level switched ultrasound pulsers using a standard NMOS-PMOS half bridge driver topology. Each driver consists of three half-bridges using SQJ431EP PMOS transistors (Vishay Siliconix) for driving to high-side positive voltages, and BSC900N20NS3 NMOS transistors (Infineon Technologies) for driving to low-side negative voltages. Two of the bridges allow driving the output to one of four power levels, with a third bridge used to clamp the output to ground. The bridge structure is shown in Fig.1.

The MOSFETs used in the system were selected to achieve the highest possible switching speeds whilst maintaining capability of a high output voltage. The specification of the HIFUARP is for an output voltage of ±80 V, requiring PMOS and NMOS breakdown voltages capable of withstanding the 160 V swing. With a minimum 200 V rating, and sufficient output power handling, despite the SQJ431EP being the fastest available PMOS transistor, it is still limited to over 44 ns turn-off delays.

## III. MODIFIED HRPWM WAVEFORM DESIGN

Harmonic Reduction Pulse Width Modulation (HRPWM) provides a methodology that enables the design of multi-level switched excitation waveform without third harmonics. Due to the relatively slow turn-on and turn-off delays associated with the high voltage, high current MOSFETs required for driving HIFU transducers limitations on dead-time must be imposed on the waveform design. Dead-time is characterized by a period of time whereby the excitation circuit output is un-driven before the transition to the next voltage level to

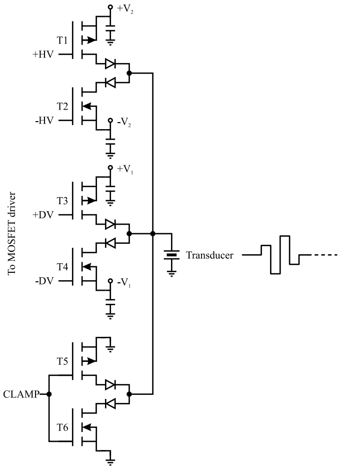


Fig. 1. Generic P and N-type MOSFET based bipolar five-level switched ultrasound excitation circuit with direct transducer connection.

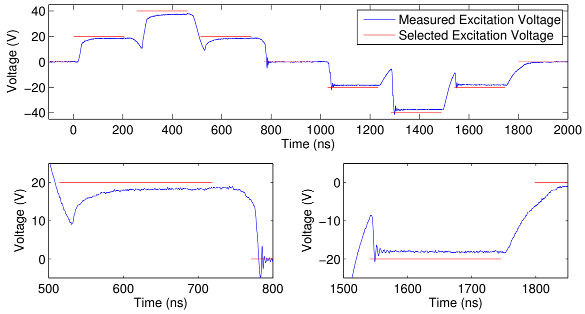


Fig. 2. Dynamic MOSFET characteristics for the five level switched HIFU excitation circuit (top). None-symmetric turn on and turn off delays for the slower SQJ431EP PMOS (lower left) and faster BSC900N20NS3 NMOS transistors (lower right).

prevent short circuiting of the MOSFETs. The largest dead-time required for the HIFUARP is for the high side transistors which require 44 ns gap, thereby imposing a minimum turn-on time. The impact of dead-time on waveform design is shown in Figs. 3 and 4 where HRPWM is indicated in white superimposed on the normalized amplitude of the first and third harmonics. The regions shown in black cannot be realized as they would violate dead-time restrictions thereby resulting in output amplitudes that cannot be achieved with HRPWM. The excitation waveform is generated from $\delta_1$ and $delta_2$ as illustrated in Fig. 5.

Relaxing the requirement for maximum possible cancellation of third harmonics during waveform deign and instead optimizing harmonic cancellation around the dead-time restricted parameters provides solutions for all output amplitudes. Modified Harmonic Reduction Pulse Width Modulation (mHRPWM) minimizes the third harmonic by searching the whole design-space as shown in Figs.3 and 4 building a non-continuous piece wise modulation path from 15% to 100% output amplitude. The mHRPWM modulation path is shown in red. The resulting mHRPWM waveform solutions are

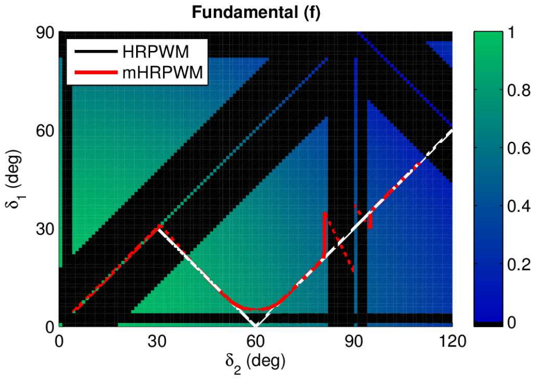


Fig. 3. Fundamental waveform design for mHRPWM based on achieving continuous amplitude control whilst minimization of third harmonic.

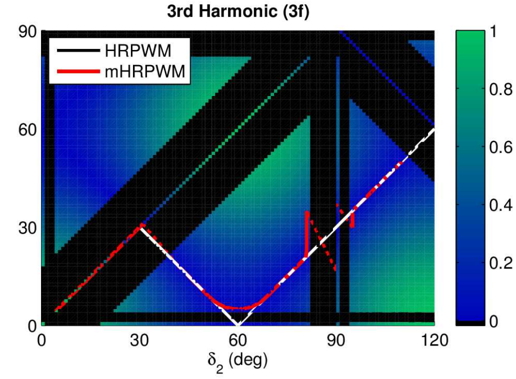
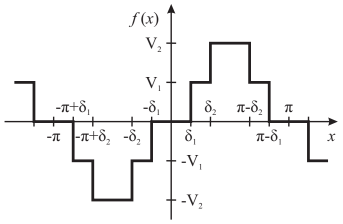


Fig. 4. Third harmonic Waveform design for mHRPWM based on achieving continuous amplitude control whilst minimization of third harmonic.

a) Physical realisation where $\delta_2 \leq \frac{\pi}{2}$



b) Physical realisation where $\delta_2 > \frac{\pi}{2}$

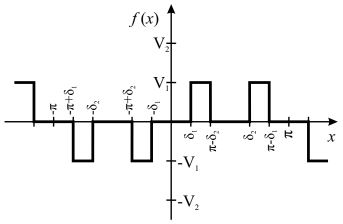


Fig. 5. Calculation of excitation waveform from $\delta_1$ and $\delta_2$.

composed of both mid and high voltage three level, five level and dual pulse mid voltage excitation cycles. The resulting modulation waveforms are compatible with the design of amplitude and frequency modulated plus arbitrary excitation waveforms.

## IV. EXPERIMENTAL RESULTS AND DISCUSSION

Using the calculated solutions, 20 cycle waveforms were generated and then uploaded to the HIFUARP which was connected to a 1.1 MHz HIFU transducer (H-102, Sonic Concepts, USA) along with its matching network. With a membrane hydrophone (Precision Acoustics, UK), the acoustic waveform at the transducer focus was recorded for each excitation along with all usable mHRPWM excitation waveforms. The transducer and hydrophone were placed in a tank of degassed and deionised water. To reduce the effects of non-linear propagation, the rail voltages, $V_2$, $V_1$, GND, $-V_1$ and $-V_2$ were reduced to 12 V, 6 V, 0 V, -6 V and -12 V respectively. Although this was lower than what would be required to generate lesioning pressures, it reduced the effects of harmonic generation as a result of nonlinear propagation. This allowed the harmonic distortion of the signal as a result of the electrical waveform to be isolated and measured.

From the recorded waveforms, the magnitude of the selected frequencies were found using an FFT. The global maximum observed peak pressure was used as a reference to represent each waveform by a decibel value, and from this the effective amplitude as a percentage of maximum was found by linear curve fitting.

Fig.6 shows the normalized spectra of the ideal waveform for 15 to 100% amplitude. The results indicated the cancellation of odd (2n) due to waveform symmetry plus complete cancellation of the third harmonic at valid HRPWM amplitudes plus significant cancellation of the third harmonic where mHRPWM is employed. Note that there is no systematic reduction of the fifth harmonic hence it remains present at most output amplitudes.

Fig.7 shows the spectra of the excitation waveforms measured at the output of the MOSFET excitation circuitry but before the HIFU transducer impedance matching circuit. Spectral distortion is present at sub-harmonic and harmonic frequencies which can be attributed to the time domain distortion due to slow rise times, turn-on or turn-off delays and anti-symmetric behaviours of P- and N-type MOSFETs. It should be noted that third harmonic distortion is present albeit at low amplitudes.

Fig.8 shows the spectra of the output of the membrane hydrophone for each excitation amplitude. The impedance matching circuit and transducer have a essentially filtered the broadband spectral distortion present in the excitation waveform. However, spectral distortion is present at both odd and even harmonics. This may be attributed in-part to non-linear propagation but more significantly third harmonic distortion is attributed to the transducers strong resonance at 3.3 MHz.

For comparison the fundamental and third harmonics data as presented in figures 6 to 8 are summarized and presented

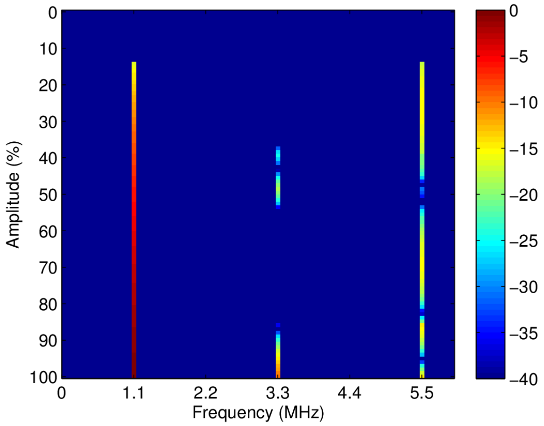


Fig. 6. Spectra for ideal mHRPWM waveform of 1.1 MHz frequency and amplitudes 15 to 100%.

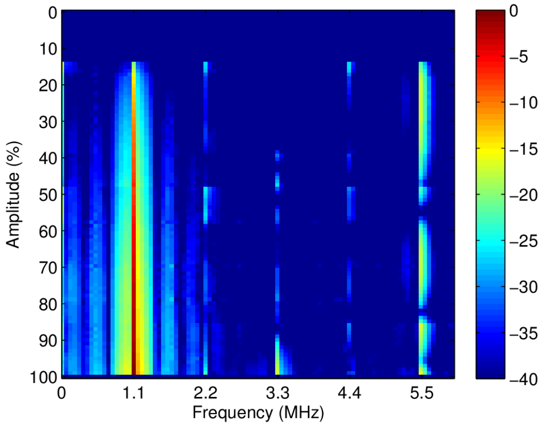


Fig. 7. Spectra for experimentally measured mHRPWM excitation waveforms of 1.1 MHz frequency and amplitudes 15 to 100%.

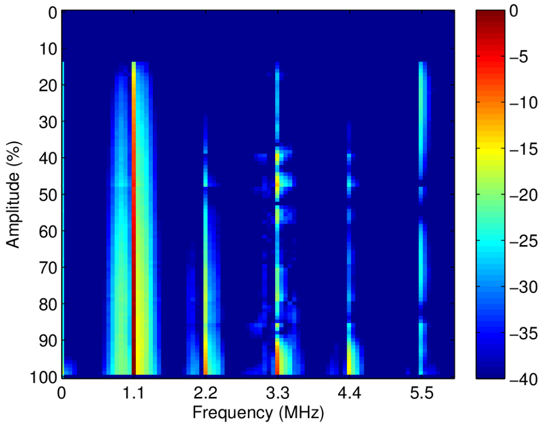


Fig. 8. Spectra for experimentally measured hydrophone waveforms based on mHRPWM excitation of 1.1 MHz frequency and amplitudes 15 to 100%.

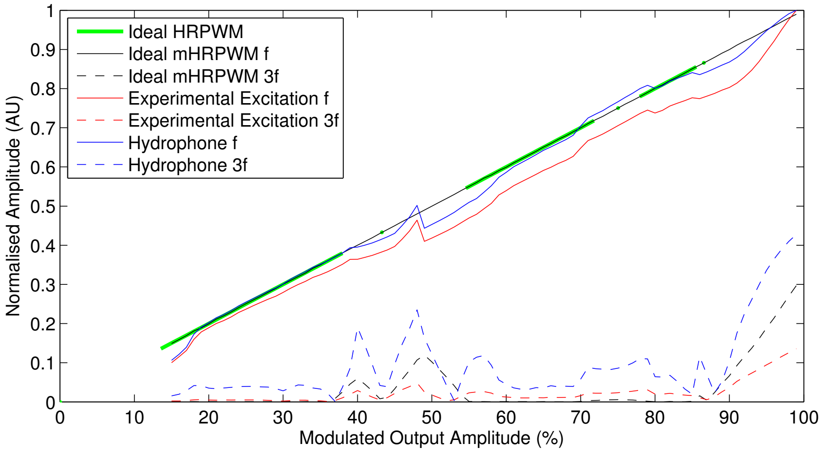


Fig. 9. Fundamental and third harmonic amplitudes of ideal waveform, excitation waveform and hydrophone measured pressure for proposed mHRPWM scheme using a 1.1 MHz HIFU transducer and HIFUARP.

against target amplitude. The ability of HRPWM to create HIFU excitation waveforms with low third harmonic content is clearly demonstrated in the regions under the green curves whereby the hydrophone measured amplitude contains harmonics of less than 5% full scale amplitude.

At amplitudes where HRPWM cannot be used due to MOSFET timing limitations the proposed mHRPWM method can be employed. Whilst conforming to the required deadtime the amplitudes 37-54% and 70-80% have can be realized with only a modest increase in third harmonic amplitude. Importantly amplitudes above 85% can now be realized, however with increased third harmonic amplitude.

Attention should be drawn to the discontinuities in the experimentally measured amplitudes of both the fundamental in excitation and hydrophone measured pressure. These discontinuities occur due to the non-ideal characteristics of the MOSFET drive circuit. It is feasible to linear the relationship between desired amplitude and actual by compensating for actual measured amplitude during the waveform design.

## V. CONCLUSIONS

mHRPWM offers a method to overcome the non-continuously variable amplitude in systems constrained by MOSFET rise, fall, turn-on and turn-off characteristics, providing a route to continuously variable output amplitude. This has been achieved by relaxing the requirement for complete cancellation of the third harmonic during the design process, instead focusing of selection of the modulation path that minimizes the third harmonic at every possible amplitude. By relaxing the requirement for complete third harmonic cancellation the maximum amplitude can be extended beyond that achievable using standard HRPWM. The proposed mHRPWM method can be adapted to the individual limitations imposed by a systems MOSFET characteristics.

mHRPWM allows the excitation amplitude to be controlled on an element by element basis in HIFU whist maintaining phasing and amplitude control. The bipolar nature of the excitation waveforms reduce any necessity for the use of transformer transducer couplings whilst the low harmonic content reduces the necessity for large external excitation waveform filtering.

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