Cowell, DMJ, Smith, P and Freear, S (2011) *Harmonic Cancellation in Switched Mode Linear Frequency Modulated (LFM) Excitation of Ultrasound Arrays.* In: Ultrasonics Symposium (IUS), 2011 IEEE International. UNSPECIFIED. IEEE , 454 - 457. ISBN 978-1-4577-1253-1

Harmonic Cancellation in Switched Mode Linear Frequency Modulated (LFM) Excitation of Ultrasound Arrays

David M. J. Cowell, Peter R. Smith and Steven Freear
Ultrasound Group, School of Electrical and Electronic Engineering
University of Leeds, Leeds, West Yorkshire LS2 9JT
Email: d.m.j.cowell@leeds.ac.uk, efy3prs@leeds.ac.uk

***Abstract*—Switched excitation is a convenient alternative to high frequency linear power amplifiers for multi-channel array systems. Unfortunately, switched mode excitation signals often contain harmonics that are undesirable in applications such as coded harmonic imaging. Harmonics can be reduced in switched excitation with the addition of intermediary voltage levels and careful control of switching timing. This work discusses two, three, five and nine level switched mode excitations suitable for Linear Frequency Modulated (LFM) coded excitation. Simulations in MATLAB compare two LFM signals with a central frequency 0.5 MHz, duration of 100 μs and bandwidths of 25% and 100% to an ideal 'analogue' case. Simulated results shows harmonic cancellation in the switched mode signals. For the nine level case, all harmonics below the 11th are cancelled. Experimental measurements are also obtained using the UARP system loaded with a 0.5 MHz transducer. Experimental results show cancellation of harmonics to -40 dB below the fundamental, however an increase in the third harmonic is apparent when comparing nine levels to five levels. To further verify harmonic reduction, calculations of the Total Harmonic Distortion are provided for each switched mode excitation up to the ninth harmonic.**

I. INTRODUCTION

The excitation system for ultrasound applications with the least harmonic distortion is an analogue excitation signal generated by a high frequency linear power amplifier in conjunction with an arbitrary waveform generator. This setup ensures excitation signal integrity and minimised harmonic distortion. The cost and size of such systems however is undesirable, especially when multiple channels are required, as in the case of ultrasound array imaging.

Switched mode excitation offers an alternative to the conventional linear power amplifier setup. Fixed voltage levels and high frequency MOSFET devices generate 'square' or 'staircase' waveforms, most often of sinusoidal form. Switched mode systems are advantageous due to their small scale, high current and high voltage capability. A disadvantage of switched excitation is the significant harmonic content inherent within the signals. These harmonics can result in a number of dissatisfactory phenomena including pressure wave distortion, energy reduction at the fundamental frequency and additional lobes in the transmitted pressure field [1].

Harmonic content in the excitation signal can also impact on imaging modalities; particularly harmonic imaging. Imaging using the second harmonic is a well established technique benefiting from increased resolution, reduced artifact sensitivity and improved image quality when compared to fundamental mode [2]. More recently, imaging using one or more higher harmonics (e.g. third, fourth or fifth) has been proposed [3]. Combining higher order harmonics can further improve axial resolution beyond the second harmonic whilst maintaining Signal-to-Noise Ratio (SNR) and is referred to as 'super harmonic imaging'.

Issues surrounding harmonic and super harmonic techniques include insufficient transducer bandwidth, transmission of unwanted excitation harmonics and the low SNR of the received harmonics [4]. The SNR of the received harmonics can be improved using coded excitation signals and pulse compression [5], [6], [7].

A popular choice of coded excitation for ultrasound are Linear Frequency Modulated (LFM) signals [8]. LFM signals can be generated using multi-level switched excitation circuits as demonstrated previously [9]. Multi-level switched excitation circuits can improve coded excitation [9] and reduce harmonic content [10].

This paper discusses switched mode LFM signals for use in coded harmonic imaging with arrays; a particularly demanding application requiring excitation signals with low levels of harmonic distortion and the use of multiple channels.

II. LFM EXCITATION

LFM signals and matched filtering techniques are commonly used in a wide range of applications to improve SNR of the received signals such as in [11] and [12]. An LFM signal can be expressed for time t as

$$\psi(t) = e^{j2\pi\left(f_0 t + \frac{B}{2T}t^2\right)} \tag{1}$$

where f_0 is the central frequency, T is the pulse duration, B is the bandwidth and t is defined from

$$-\frac{T}{2} \leq t \leq \frac{T}{2}.$$

The instantaneous frequency f_i of LFM signals increases linearly with respect to time. The instantaneous frequency of the LFM signal (1) can be calculated by taking the derivative of the phase

$$f_i(t) = \frac{d}{dt}\left(f_0 t + \frac{B}{2T}t^2\right) = f_0 + \frac{B}{T}t. \tag{2}$$

Often, the complex LFM signal described in (1) is windowed in the time domain using an envelope function $a(t)$, resulting in the excitation signal, $\mu(t)$.

$$\mu(t) = a(t) \cdot \psi(t) \tag{3}$$

Windowing the signal in the time domain reduces sidelobes in the filtered response and increases dynamic range [8]. A theoretical analysis of a wide range of appropriate window functions can be found in [13].

III. Switched Mode Excitation

In its simplest form, only two voltage levels are necessary for switched excitation. A disadvantage of switched mode methods, particularly with a small number of voltage levels (e.g. two or three) is the high harmonic content, as the resulting square wave is a poor approximation of a sinusoidal waveform. In two level excitation, harmonic content cannot be reduced, however the use of three level excitation permits a choice of switching instant. This choice, provided by the additional levels, can be exploited to reduce the harmonic content of the signal as demonstrated by Tang and Clement [10]. An additional benefit of multi-level switched mode excitation is that it enables windowing of the excitation sequence in the time domain as described in (3) and discussed in more detail in [9].

When switching is performed using MOSFET devices, the number of MOSFETs required $N' = N + 1$ where N is the number of discrete levels. The additional MOSFET is required as two devices are necessary to realise the zero volt level. Advances in integrated circuits specifically targeted at ultrasound medical imaging, combines a number of high voltage MOSFET switches packaged into a single low cost device. This facilitates the design of circuits with multiple levels as shown in Figure 1.

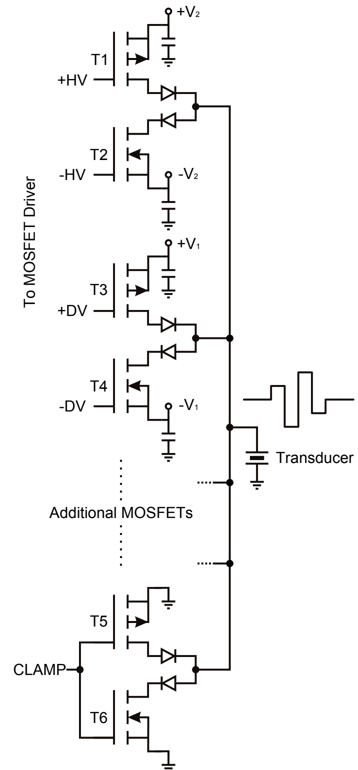

Fig. 1. Generalised MOSFET-based circuit for multi-level switched mode excitation.

IV. Simulated Performance of Switched Mode LFM Signals

Simulations in MATLAB (Mathworks Inc., Natick, MA, USA) of switched mode LFM signals demonstrate the correlation between increasing the number of voltage levels and harmonic cancellation. Figure 2 shows switched mode LFM signals as described in (1) of f_0=0.5 MHz, T=100 μs and B=0.125 MHz (25% bandwidth). These parameters were chosen so that the harmonics were separate and distinct, and to maximise the ratio of sampling frequency to center frequency in the experimental observations (presented in the next section). To clarify, only a subsection of the excitation signal has been shown in each time domain plot so that the number of levels can be visualised. The excitation spectrum for the two level case in Figure 2 demonstrates the most harmonic content, with a third harmonic -16 dB below the fundamental, a fifth harmonic at -23 dB, a seventh harmonic at -27 dB and a ninth harmonic at -30 dB. In the simulated cases, the additional levels provide both harmonic cancellation and reduction of the harmonics that are still present. It can be seen that nine level excitation reduces harmonic content to below -60 dB up to the wide bandwidth eleventh harmonic centered around 5.5 MHz.

When B is increased to 0.5 MHZ (100% bandwidth), the harmonics overlap as shown in Figure 3. Simulated results show a decrease in the overall harmonic noise floor from -20 dB in the two level case to -35 dB in the nine level case. This is also seen in the analogue simulation, however the eleventh harmonic is not present.

V. Experimentally Measured Performance of Switched Mode LFM Signals

Simulations of harmonic cancellation were validated with experimental measurements. Switched mode LFM signals of two, three, five and nine levels were generated using the University of Leeds, Ultrasound Array Research Platform (UARP) [14]. A single channel was loaded with a piston-type transducer (IDHF0.58R, 1.0 inch diameter, NDT Systems Inc. Huntington Beach, CA) and transducer loaded LFM excitation signals were captured with a LeCroy Waverunner 64Xi digital oscilloscope (LeCroy Corporation, Chestnut Ridge, NY, USA).

A. Experimental Waveforms

Figures 4 and 5 show the experimentally measured time domain waveforms and spectra for the 25% and 100% bandwidth

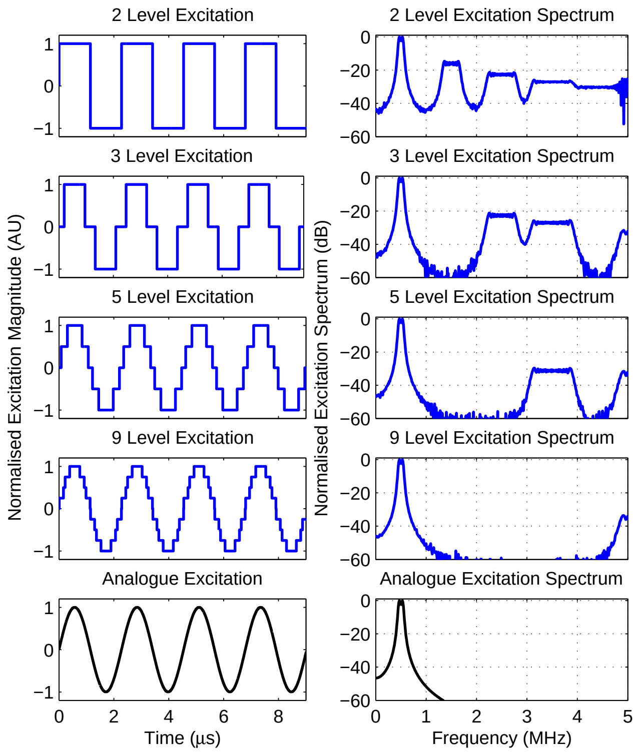

Fig. 2. Simulation of two, three, five and nine level switched mode LFM signals of f_0=0.5 MHz, T=100 μs and 25% bandwidth (B=0.125 MHz). An ideal 'analogue' waveform is also shown for comparison.

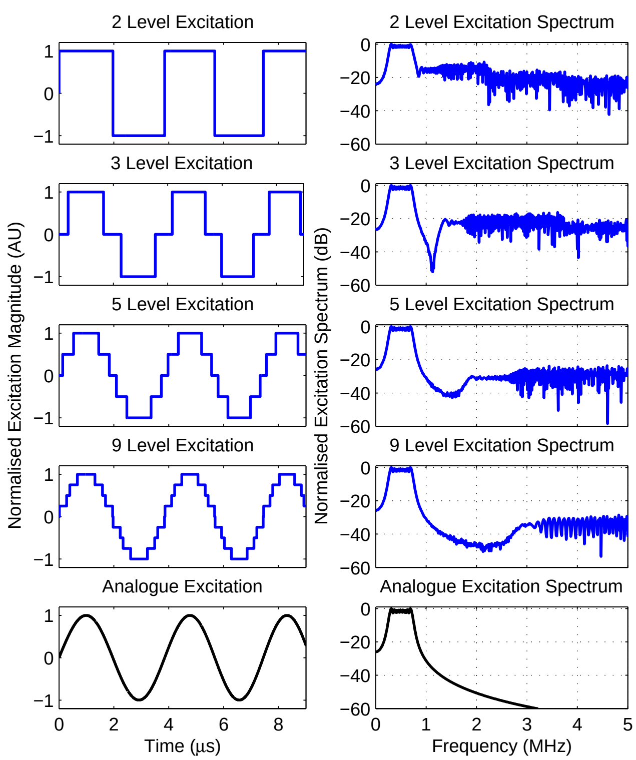

Fig. 3. Simulation of two, three, five and nine level switched mode LFM signals of f_0=0.5 MHz, T=100 μs and 100% bandwidth (B=0.5 MHz). An ideal 'analogue' waveform is also shown for comparison.

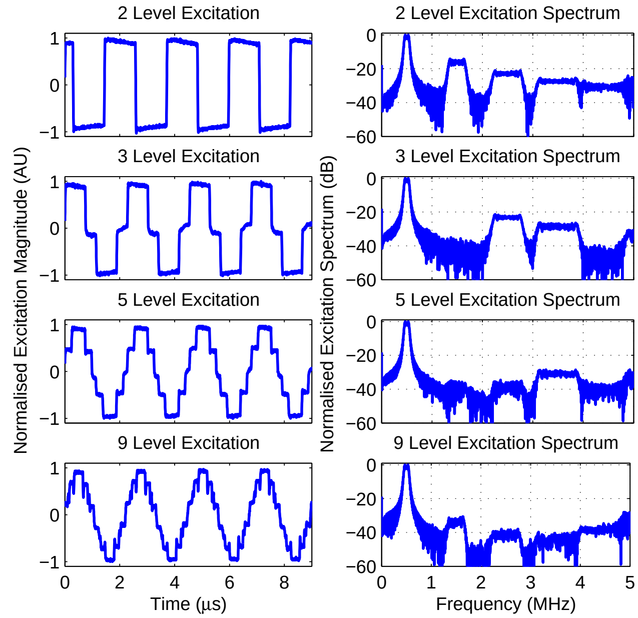

Fig. 4. Normalised experimental data using the UARP system of two, three, five and nine level switched mode LFM signals of f_0=0.5 MHz, T=100 μs and 25% bandwidth (B=0.125 MHz).

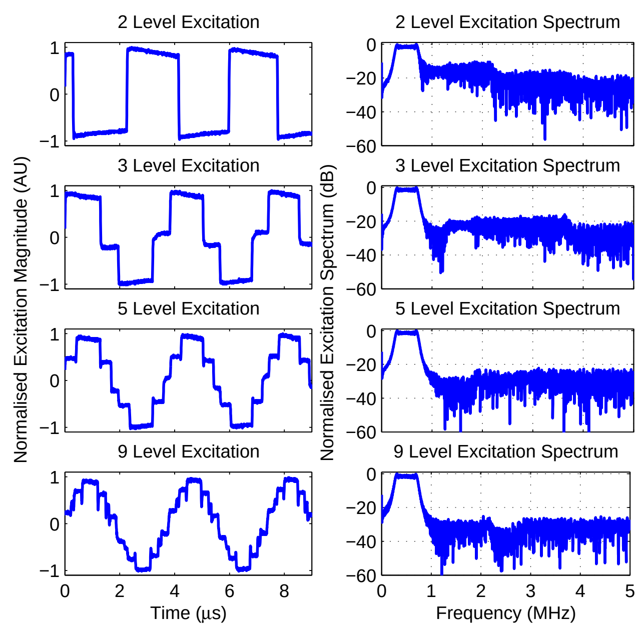

Fig. 5. Normalised experimental data using the UARP system of two, three, five and nine level switched mode LFM signals of f_0=0.5 MHz, T=100 μs and 100% bandwidth (B=0.5 MHz).

cases respectively. Both figures confirm harmonic cancellation as a result of increasing the number of switching levels, with harmonics being suppressed to -40 dB in the 25% bandwidth case, and -30 dB in the 100% bandwidth case.

Also evident in the figures however is a rise in the third harmonic ($3f_0$ at 1.5 MHz) in the nine level case when compared with the five level case. This is unexpected when compared with simulation.

B. Total Harmonic Distortion

In order to further demonstrate the overall reduction in harmonic content, the Total Harmonic Distortion (THD) has been calculated for each of the experimentally measured LFM signals where THD is defined as

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} \tag{4}$$

and V_n is the voltage level corresponding to the n-th harmonic. Because of the bandwidth of the LFM signals, values for V_n have been chosen at integer multiples of f_0. THD results up to n=9 are displayed in Table I. Results show that the use of a wider bandwidth signal increases THD as a result of overlapping harmonics, however THD decreases when additional levels are included.

TABLE I
CALCULATED THD FROM EXPERIMENTAL RESULTS (UP TO n=9).

	2 Level	3 Level	5 Level	9 Level
25% LFM	20.1%	9.0%	4.0%	2.9%
100% LFM	39.6%	21.2%	10.4%	8.0%

VI. DISCUSSION AND CONCLUSION

Multi-level switched mode LFM signals with reduced harmonic content are presented for use in coded excitation. By introducing multiple switching levels and with careful choice of switching time, a direct relationship between the number of switching levels and harmonic cancellation can be exploited.

Simulations of two, three, five, and nine level excitations are compared with an ideal analogue sinewave to simulate the expected output from a linear power amplifier and arbitrary waveform generator. Simulations of LFM signals with 25% and 100% show suppression of harmonics to -60 dB levels with systematic cancellation of odd harmonics with increasing number of excitation voltage levels. These results have been confirmed with experimental measurements using the MOSFET based transmitter of the UARP system.

Experiments show reduction of harmonics, to below -40 dB, however when nine levels are used there is an increase in the level of the third harmonic. The authors believe this occurs in the nine level case because of inaccuracies in switching due to time sampling of the excitation control system. These inaccuracies become increasingly significant as more levels are included, leading to an increased number of voltage transitions. In order to verify whether the increase in the third harmonic compromises harmonic reduction the THD of each LFM signal was evaluated. THD results confirm that additional switching levels reduce harmonic power.

The proposed excitation is targeted towards harmonic imaging applications using array systems consisting of multiple channels. In these applications, high frequency linear power amplifer based systems are unsuitable due to their size, complexity and cost. Switched mode systems provide a practical alternative.

REFERENCES

[1] R. S. Cobbold, *Foundations of Biomedical Ultrasound.* Oxford University Press, 2007.

[2] A. Bouakaz and N. de Jong, "Native tissue imaging at superharmonic frequencies," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 50, no. 5, pp. 496 –506, may 2003.

[3] A. Bouakaz, B. J. Krenning, W. B. Vletter, F. J. ten Cate, and N. D. Jong, "Contrast superharmonic imaging: A feasibility study," *Ultrasound in Medicine & Biology*, vol. 29, no. 4, pp. 547 – 553, 2003.

[4] G. Matte, P. Van Neer, M. Danilouchkine, J. Huijssen, M. Verweij, and N. De Jong, "Optimization of a phased-array transducer for multiple harmonic imaging in medical applications: frequency and topology," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 58, no. 3, pp. 533 –546, march 2011.

[5] J. Borsboom, C. T. Chin, A. Bouakaz, M. Versluis, and N. de Jong, "Harmonic chirp imaging method for ultrasound contrast agent," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 52, no. 2, pp. 241 –249, feb. 2005.

[6] M. Arif, D. M. J. Cowell, and S. Freear, "Pulse compression of harmonic chirp signals using the fractional fourier transform," *Ultrasound in Medicine & Biology*, vol. 36, no. 6, pp. 949 – 956, 2010.

[7] M. G. Danilouchkine, P. L. M. J. van Neer, G. M. Matte, M. M. Voormolen, M. D. Verweij, and N. de Jong, "Superharmonic imaging based on chirps," in *Ultrasonics Symposium (IUS), 2010 IEEE*, oct. 2010, pp. 2195 –2198.

[8] T. Misaridis and J. Jensen, "Use of modulated excitation signals in medical ultrasound. part I: basic concepts and expected benefits," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 52, no. 2, pp. 177 –191, feb. 2005.

[9] D. M. J. Cowell and S. Freear, "Quinary excitation method for pulse compression ultrasound measurements," *Ultrasonics*, vol. 48, pp. 98–108, 2008.

[10] S. C. Tang and G. Clement, "A harmonic cancellation technique for an ultrasound transducer excited by a switched-mode power converter," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 55, no. 2, pp. 359 –367, feb. 2008.

[11] S. Harput, T. Evans, N. Bubb, and S. Freear, "Diagnostic ultrasound tooth imaging using fractional fourier transform," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 58, no. 10, pp. 2096 –2106, oct. 2011.

[12] D. M. J. Cowell and S. Freear, "Separation of overlapping linear frequency modulated (lfm) signals using the fractional fourier transform," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 57, no. 10, pp. 2324 –2333, oct. 2010.

[13] F. Harris, "On the use of windows for harmonic analysis with the discrete fourier transform," *Proceedings of the IEEE*, vol. 66, no. 1, pp. 51 – 83, jan. 1978.

[14] P. R. Smith, D. M. J. Cowell, B. Raiton, C. V. Ky, T. H. Pham, B. Q. Bui, and S. Freear, "A pll-based phased array method to minimize phase quantization errors and reduce phasing-lobes," in *Ultrasonics Symposium (IUS), 2010 IEEE*, oct. 2010, pp. 1837 –1840.