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Quinary excitation method for pulse compression ultrasound measurements

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Abstract

A novel switched excitation method for linear frequency modulated excitation of ultrasonic transducers in pulse compression systems is presented that is simple to realise, yet provides reduced signal sidelobes at the output of the matched filter compared to bipolar pseudo chirp excitation. Pulse compression signal sidelobes are reduced through the use of simple amplitude tapering at the beginning and end of the excitation duration. Amplitude tapering using switched excitation is realised through the use of intermediate voltage switching levels, half that of the main excitation voltages. In total five excitation voltages are used creating a quinary excitation system. The absence of analogue signal generation and power amplifiers renders the excitation method attractive for applications with requirements such as a high channel count or low cost per channel. A systematic study of switched linear frequency modulated excitation methods with simulated and laboratory based experimental verification is presented for 2.25 MHz non destructive testing immersion transducers. The signal to sidelobe noise level of compressed waveforms generated using quinary and bipolar pseudo chirp excitation are investigated for transmission through a 0.5 m water and kaolin slurry channel. Quinary linear frequency modulated excitation consistently reduces signal sidelobe power compared to bipolar excitation methods. Experimental results for transmission between two 2.25 MHz transducers separated by a 0.5 meter channel of water and 5% kaolin suspension shows improvements in signal to sidelobe noise power in the order of 7 to 8 dB. The reported quinary switched method for linear frequency modulated excitation provides improved performance compared to pesudo chirp excitation without the need for high performance excitation amplifiers.

Key words: Pulse compression, ultrasound, linear frequency modulation, industrial process measurement, high attenuating media

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1 Introduction

Ultrasound is an attractive sensing modality for industrial applications. The received signals are information rich. Indirect measurements can be made of a range of industrial variables through analysis of attenuation and velocity data. It is well known that ultrasound is able to provide spatial information as well as measurements including, but not limited to, the flow of gasses and liquids, temperature, pressure, concentrations and mixtures. Spatial reconstruction of ultrasonic data can be performed using transmission and reflection modes to generate tomographic reconstructions of the variable of interest. Measurements may be made invasively where transducers have direct contact with the measured material or non-invasively where additional interfaces exist between the transducers and the measured material.

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Obstacles exist to making accurate ultrasound measurements. There are many power loss mechanisms for the ultrasound signals, including scattering and absorption within the materials, beam spreading, and inefficiencies within the transducer and measurement system. In industrial systems, high signal attenuation may be encountered due to a combination of highly attenuating material and long path lengths. Where an acoustic impedance mismatch occurs between the transducer, vessel wall and content, the attenuation may be so great that the signal power drops below the systems signal to noise ratio and is hence undetectable with traditional signal processing techniques, such as envelope detection.

Where high attenuation is a problem, the power of the received signal may be improved by increasing the power of the transmitted signal. The transducers and excitation system place limits on the maximum operating power of an ultrasound system. A simple pulsed system is therefore not always capable of supplying the energy required to enable signal detection.

Rather than delivering the total excitation energy in a single pulse, spread energy excitation provides a means to increase the excitation energy without increasing the instantaneous power by extending the excitation duration. Where spread energy excitation is utilised the received signals are extended in duration and can not directly provide accurate spatial information.

Continuous wave (CW) or tone burst excitation is a spread energy system but contains little spatial information. By encoding a recognisable signature into the excitation waveform a matched filter can be used to identify the signature and compress the received signals into a single peak. Figure 1 contrasts pulsed excitation and spread energy excitation using a linear frequency modulated

(LFM) signal.

INSERT FIGURE 1 HERE

Pulse compression systems are more complex to implement than pulsed systems. A pulsed system requires a simple switched excitation system, a band pass filter, and typically an envelope filter on the receiver. A pulse compression system requires a more complex excitation system. For maximum control a digital controller, a high speed digital to analogue converter (DAC) and a broadband precision power amplifier as a transmitter. The receiver requires a high speed analogue to digital converter (ADC) and a matched filter utilising complex arithmetic.

The ideal output of the matched filter is a single narrow peak when each ultrasound signal is detected, in practice the main peak is accompanied by sidelobes. With careful excitation the power of these sidelobes can be controlled and hence minimised. Signal to sidelobe noise ratio (SSNR) is the ratio of the magnitude of the main peak to that of the sidelobes. SSNR needs to be maximised to reduce the likelihood of false detection and measurement of a sidelobe rather than the main peak. SSNR is illustrated in figure 2 where the analytic pulse compression waveform has a SSNR of 13.5 dB.

INSERT FIGURE 2 HERE

It is possible to maximise the SSNR by controlling the excitation signals applied to the transmitting transducer. Tapering of the signal envelope combined with analogue excitation helps to improve the SSNR. When the excitation signal is not carefully controlled, for example when switched pseudo chirp rather than analogue excitation is used, the pulse compression system has a reduced

SSNR as high power sidelobes are present.

Although pulse compression techniques have been used successfully in radar systems to increase range and resolution since the 1950s [1], the first person to propose the use of pulse compression techniques with ultrasound was Takeuchi in 1979 [2]. He proposed the use of linear frequency modulated (LFM) excitation and binary coded excitation using Golay codes as a method to overcome restraints of resolution, peak power and penetration.

Recently papers have been published where LFM pulse compression has been used with wideband air-coupled transducers for NDT [3,4] and surface monitoring of wood samples [5].

Medical ultrasonic systems have seen widespread interest in pulse compression systems, Misaridis published a comprehensive introduction series to medical pulse compression [6,7,8] whilst other introduction and developers guides have been published [9,10]. Bridging the gap between NDT and medical systems have been papers monitoring bone thickness and density [11,12].

The optimisation of excitation signals to reduce peak width and sidelobe power has been discussed in detail [13] whilst optimising the excitation bandwidth for different transducers has also been investigated [14].

This paper provides a mathematical introduction to LFM pulse compression systems. The effect of ultrasonic transducers and received signal to noise ratio (SNR) are illustrated using simulated and experimental results. A novel five level, quinary, pseudo-chirp excitation system is presented with improved sidelobes compared to traditional pseudo-chirp excitation systems. Finally, an industrial scale demonstration compares and contrasts traditional pseudo-chirp excitation with quinary excitation.

2 Pulse Compression and LFM Excitation

2.1 Excitation signal design

A linear FM signal can be expressed for time t as

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

where f_0 is the central frequency, T is the pulse duration and B the bandwidth. The instantaneous frequency f_i of the system is the derivative of the phase, indicating that the instantaneous frequency is linear with respect to time

$$\begin{aligned} f_i(t) &= \frac{d(f_0 t + \frac{B}{2T}t^2)}{dt} \\ &= f_0 + \frac{B}{T}t, \quad -\frac{T}{2} \leq t \leq \frac{T}{2}. \end{aligned} \tag{2}$$

The complex LFM signal (1) is windowed in time and magnitude, using an envelope of $a(t)$,

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

At its simplest the envelope is rectangular, but, more complex envelopes to taper the signal may be beneficial as described in section 2.4.2. The real part of the complex signal applied to the transducer $\eta(t)$ as an excitation waveform

$$\eta(t) = a(t) \cdot \Re\left(\psi(t)\right). \tag{4}$$

The same complex signal, $\mu(t)$, is used during design of the pulse compression filter.

2.2 Ultrasound channel effects

When the LFM excitation signal is applied to the transmitting transducer, the resulting RF waveform [13] at the receiver is

$$\begin{aligned} u(t) = & \eta(t) * g_{tx}(t) * H_{tx}(t) * f_{scat}(t) * h_a(t) \\ & * g_{rx}(t) * H_{rx}(t) \end{aligned} \tag{5}$$

where $g_{tx}(t)$ and $g_{rx}(t)$ are the impulse responses of the transmit and receive transducers, $H_{tx}(t)$ and $H_{rx}(t)$ are the impulse responses of the transmit and receive circuits, and f_{scat} and $h_a(t)$ the impulse of the scatters and medium respectively.

Convolution in the time domain is equivalent to multiplication in the frequency domain. If the windowed excitation signal (4) is substituted into (5) and converted to the frequency domain,

$$\begin{aligned} u(f) = & \left(\frac{1}{2\pi} a(f) * \Re\left(\psi(f)\right) \right) \\ & \cdot g_{tx}(f) \cdot H_{tx}(f) \cdot f_{scat}(f) \cdot h_a(f) \\ & \cdot g_{rx}(f) \cdot H_{rx}(f), \end{aligned} \tag{6}$$

it becomes apparent that windowing of the excitation signal cannot be replaced by windowing of the received signal at a filtering stage. Additional factors such as non-linear wave propagation, interference, near and far field effects, beam spreading and transducer geometry, would have to be considered to fully model an ultrasonic system.

2.3 Pulse compression filter design

The pulse compression filter (PCF) is a linear time-invariant (LTI) filter that compresses the received ultrasound signal whilst maximising the SNR of the receiver output in the presence of white Gaussian noise. In this paper the implementation of the PCF is a matched filter. In its simplest form the impulse response $h(t)$ of the PCF is the time reversed, complex conjugate of the excitation waveform, except for a gain factor, k, and depending on the implementation of the filter, a time delay τ_d. Thus the impulse response of the complex PCF, $h(t)$ is

$$h(t) = k \cdot \mu^*(\tau_d - t), \tag{7}$$

thus the frequency response $H(f)$ of the filter is

$$H(f) = ke^{-j2\pi f \tau_d} \cdot \mu^*(f). \tag{8}$$

In some applications a mismatched filter may be used where additional windowing or adjustment of the filter coefficients provide improved signal compression.

Using convolution theory, the output of the PCF is

$$\gamma(\tau) = \int_0^\infty h(t)\mu(\tau - t)dt = k \int_0^\infty \mu^*(t)\mu(\tau - t)dt. \tag{9}$$

When the input to the PCF is the complex excitation signal without the effects of the ultrasound transducers and channel, the output of the matched filter, $\gamma(\tau)$, is equal to the autocorrelation of the excitation signal, except for a time shift of τ_d. The PCF can be realised digitally as a finite impulse response (FIR) filter where all calculations are complex.

An analytical solution of the matched filter output, $R_{\mu\mu}(\tau)$, when no transducer or channel is present can be calculated [7] by substituting (1) into (9).

$$R_{\mu\mu}(\tau) = T \cdot e^{j2\pi f_0 \tau} \cdot \frac{\sin\left[\pi T B \frac{\tau}{T}\left(1 - \frac{|\tau|}{T}\right)\right]}{\pi T B \frac{\tau}{T}}, \tag{10}$$

the result of which can be used as a benchmark of ideal performance. A similar proof of which can be found in standard radar texts [1,15,16].

Analysis of the pulse compression process can also be performed in the frequency domain, which may be simpler to visualise. As illustrated in figure 3, the LFM excitation wave (3) represented in the frequency domain has an amplitude of rectangular shape, but due to the low time bandwidth product of the system, Fresnel ripples exist in the frequency domain. These ripples are reduced as the time bandwidth product of the excitation is increased. The PCF coefficients are the time reversed complex conjugate of the excitation signal. In the frequency domain, the amplitude of the matched filter coefficients are identical to that of the excitation wave, whilst the phase is identical in magnitude but negative. In the frequency domain, the filtering process is performed by multiplying the complex frequencies together. The amplitude is squared, whilst the positive and negative phases cancel each other out leaving zero phase.

INSERT FIGURE 3 HERE

Using an inverse Fourier transform of the resulting frequency domain waveform produces a sinc-like waveform in the time domain as might be expected from (10).

The excitation duration, T, has little effect on the shape of the PCFs output, and hence the time resolution, but, by increasing T, more energy can be transferred into the system. Often the first zero of $R_{\psi\psi}$, is used as a measure of time resolution τ_r for a LFM signal [17] and is approximated by

$$\tau_r \approx \frac{1}{B}. \tag{11}$$

Thus the axial resolution is a function of bandwidth and is independent of excitation duration. For the same bandwidth, pulsed and coded ultrasound have the same axial resolution. In coded ultrasound, the output from the matched filter approximates a sinc function. These signal sidelobes can mask smaller signals and hence need to be suppressed to reduce the chance of false measurements.

2.4 Simulated Results

Before implementing the pulse compression system in hardware, simulations were carried out using Matlab. By simulating the effect of the transducer transfer function and input noise on the pulse compression mechanism, a benchmark was created for comparison with experimental results.

2.4.1 Effect of transducer transfer function on the pulse compressor output

To optimise the process of pulse compression in an ultrasound system the transducer must first be considered. Each transducer has a fixed central frequency, limited bandwidth, damping and sensitivity. The precise characteristics vary between manufacturers and no two transducers are the same. By examining the impulse response of the transducer in both the time and frequency domains it's effects on the ultrasound system can be simulated. Our simulations and subsequent experimentation use 2.25 MHz immersion transducers manufactured by Panametrics, with a 3 dB bandwidth of 1.07 MHz from 1.85 to 2.92 MHz. These transducers have an impulse and frequency response as shown in figure 4. When exciting the transducers with a broadband waveform of rectangular envelope, such as an LFM signal, the transducers frequency response approximates a bandpass filter and hence the transducer only responds to excitation frequencies within it's bandwidth.

Figure 5 illustrates the effect of the transducer on the matched filter output by comparison with a simulation in which the transducer is not taken into effect. The effect of the transducers limited bandwidth and oscillatory response is a non-symmetric widening of the main pulse and introduction of large sidelobes. Since the transducer imposes such limitations on the performance of the pulse compression process its transfer function must be included in any simulation.

INSERT FIGURE 4 HERE

INSERT FIGURE 5 HERE

When excited with a signal of rectangular envelope, the received signal shows a region where the response approximates the transducer impulse response both before and after the LFM response. This is due to the sharp rise and fall time at the beginning and end of excitation. The natural response of the transducer to the initial excitation is a broadband response after which the transducer is driven at the desired frequency if it is within the bandwidth of the transducer.

2.4.2 Excitation tapering to reduced distortion

A received waveform illustrating this effect and the associated matched filter output is illustrated in figure 6. This distortion will be suppressed by tapering the envelope of the excitation signal with a raised cosine envelope. The same excitation waveform with additional tapering at a factor of 0.25 and matched filter output is shown in figure 7. The use of a raised cosine window reduces the power of the far sidelobes generated by the matched filter process from -27.2 dB to -49.8 dB, an improvement of 22.6 dB.

INSERT FIGURE 6 HERE

INSERT FIGURE 7 HERE

2.4.3 Effect of noise on the pulse compressor output

LFM excitation and pulse compression is suited for use in ultrasound systems where the received signal is corrupted with a high level of noise and hence has a low SNR. Matched filters have the ability to maximise SNR at their output whilst performing pulse compression. The matched filter achieves this by calculating the likelihood that the matching signal is present at each calculation instance. As such, Gaussian white noise is statistically reduced at the output of the matched filter. With decreasing input SNR the SNR of the output is also reduced.

Many variables effect the SNR of the matched filters output. These include the time-bandwidth product of the matching signal, sampling frequency and ultrasound channel effects including the transducers impulse response. As such, it is impractical to predict the exact response of the matched filter in every circumstance. Increasing the bandwidth, excitation duration and the sampling frequency all improve the output SNR.

For example, if a LFM signal of 2.5 MHz bandwidth, 2.25 MHz central frequency and 10 μs duration, sampled at 100 MHz is corrupted with Gaussian white noise to produce a signal with a SNR of -6.43 dB, signal detection without the pulse compression process is not possible. After pulse compression, the output signal, figure 8, has a SSNR of 8.35 dB, an improvement of 14.78 dB.

INSERT FIGURE 8 HERE

3 Hardware implementation of LFM Pulse Compression

Experimental verification of the LFM excitation and pulse compression simulations is required. Since industrial applications are the focus of this research, an experimental set up suitable for industrial implementation is required. As such, the ultrasound system must be small, low cost, reliable and high performance. Three solutions for LFM excitation are presented, one a complex analogue system, one a bipolar plus ground, 3 level, MOSFET switched solution and finally a novel, 5 level, quinary switched MOSFET system.

3.1 Analogue LFM excitation

Analogue excitation, as previously simulated, affords maximum control of the transducers output. An optimal excitation waveform can be established during simulations hence excitation utilises the maximum bandwidth of transducers to produce the narrowest pulse compression peaks whilst careful envelope shaping minimises sidelobes. Excitation harmonics are minimised and complex excitation signals can be generated with ease. Although analogue excitation offers maximum control, its implementation is complex.

3.1.1 Hardware

To excite a transducer with an analogue LFM signal, first a high speed digital controller with a digital to analogue (DAC) converter is required. The low voltage, low power output from the DAC must be amplified both in voltage and power. Often high currents are required to excite a transducer. Experimentation using various transducers has shown that often a current up to 2 amps is required to drive a 2.25 MHz transducer. A power amplifier with a bandwidth of 5 MHz, current of 2 amps, and output voltage of ±12 V has been built to demonstrate the analogue LFM excitation technique. However, to fully exploit this processing gain of the LFM pulse compression system, higher excitation voltages in the order of those found in pulsed excitation are required. An alternative to analogue excitation, where high specification excitation amplifiers are not required, is bipolar pulsed LFM excitation.

3.2 Bipolar pulsed LFM excitation

Pulsed, high power, excitation is possible using a simple switched high voltage power supply. Single pulses or tone bursts are can be used to increase excitation energy but contain little spatial information resulting in wide output pulses when used in a pulse compression system.

A simple extension of pulsed excitation is pseudo-chirp excitation. A series of pulses of linearly increasing frequency are utilised to provide high power LFM excitation. The square pulses that form pseudo-chirp excitation contain high magnitude harmonics of the excitation frequencies. Although the finite bandwidth of the transducer results in the partial suppression of these harmonics they still exist on the transducer output as piezoelectric ultrasound transducers can be driven at harmonic frequencies.

One benefit of using pseudo-chirp excitation is that it can be realised using a series of simple high voltage switches thus eliminating the requirement for high specification excitation amplifiers. The requirements for the system controller are greatly reduced, only the instantaneous polarity of the excitation is required rather than a parallel digital signal to drive a DAC.

3.2.1 Simulation

Simulation of bipolar pseudo chirp excitation has been performed in Matlab. The bipolar pseudo chirp has a central frequency of 2.25 MHz, bandwidth of 3 MHz and duration of 10 μs. Three voltages are employed, negative, ground and positive, with the ground level being defined by a signal level within $\pm 10\%$ of the maximum signal range. The simulation is based on the response of the 2.25 MHz immersion transducer described in section 2.4.1. The simulated excitation waveform, received ultrasonic signal and pulse compressor output are shown in figure 9. The received, uncompressed, ultrasound waveform shows distortion at approximately 3 and 12 μs, this distortion causes the output of the pulse compression filter to have a SSNR of -18.6 dB.

INSERT FIGURE 9 HERE

3.2.2 Hardware

Implementation of a pseudo-chirp system can be achieved using two or four MOSFETs as switches driven by a digital controller. In a two MOSFET system one MOSFET controls the positive switching and one controls the negative. One disadvantage of this arrangement is that after excitation the transducer, due to its capacitive construction, will remain charged.

A system can be implemented where a third and fourth MOSFET switch the transducer to ground when excitation is complete and is termed a return to zero (RTZ). A RTZ system is beneficial in a pulse echo system where the grounding MOSFETs prevent the transducer from remaining charged, preventing the transducer from being used in a receiving mode. This configuration is illustrated as figure 10.

INSERT FIGURE 10 HERE

3.2.3 Results

A ±100 volt, four MOSFET, RTZ system was constructed to excite a piezoelectric immersion transducer with central frequency 2.25 MHz. An identical transducer was arranged in a pitch-catch configuration with a separation of 23 mm between the faces and a tap water channel to verify the performance of the bipolar pulsed LFM excitation. The transmitting transducer was excited with an waveform of 10 μs duration and 3 MHz bandwidth. The output of the receiving transducer was digitised by a LeCroy WaveRunner 44Xi digital oscilloscope using a 1 MΩ input. Pulse compression was performed off line using Matlab software.

Although bipolar pulsed LFM excitation modulates the instantaneous frequency with time, the response of the transducers is less than perfect. The response to the initial and final voltage steps of the excitation waveform is that of the transducers impulse response. At the beginning and end of the transducers response a broadband pulse as seen on figure 11 at 6 μs and 14 μs. These broadband pulses, after pulse compression, manifest as high magnitude sidelobes (-16.34 dB) and as such are not desired. This effect is described in section 2.4.2. Sidelobes should be suppressed or eliminated as they can often mask reflections of smaller magnitude or lead to measurement errors.

INSERT FIGURE 11 HERE

3.3 Quinary pulsed LFM excitation

As a method to reduce the distortion leading to high power sidelobes associated with bipolar pseudo-chirp excitation, a quinary excitation scheme is proposed.

The initial and final change of excitation voltage when a pulsed excitation is used, generates a response like the broadband impulse response of the transducers. This broadband response must be suppressed. One method to suppress this effect is to taper the excitation waveform so that the excitation has a soft start and finish. A raised-cosine envelope around the excitation signal generates the required response.

If a bipolar pulsed excitation wave is used there is no way to apply a window to the excitation waveform. As such, a quinary excitation system with excitation voltages of ± 50 V and ± 100 V and ground is proposed. The addition of a ± 50 volt excitation level enables the initial and final excitation pulses to be of lower magnitude and hence reduce their effect. Although crude, these additional voltage levels are able to act as a simple tapering system.

Thresholding is applied to a digital RSC windowed LFM waveform. Figure 12 illustrates threshold levels of ±0.8 and ±0.2 for the ±100 V and ±50 V excitation levels and subsequent soft start of the excitation period.

INSERT FIGURE 12 HERE

3.3.1 Simulation

The effect of the quinary excitation has been evaluated by comparison with bipolar excitation of the same parameters. In keeping with the excitation parameters used in section 3.2.3, a central frequency of 2.25 MHz, bandwidth of 3 MHz, duration of 10 μs plus an additional raised cosine window of coefficient 25% to taper the beginning and end of the excitation waveform.

INSERT FIGURE 13 HERE

By comparison of figures 9 and 13 it can be seen that distortion at the start and end of the excitation period has been reduced by the implementation of the quinary excitation system. Using quinary excitation the signal sidelobes are -29.3 dB, a reduction of 10.7 dB compared to bipolar excitation.

3.3.2 Hardware

The hardware required to realise a quinary system is a variant of a bipolar system. Figure14 shows the additional MOSFETs, T3 and T4, that implement the intermediate voltage levels.

INSERT FIGURE 14 HERE

3.3.3 Results and discussion

Experimental verification of the effect of quinary excitation has been performed. Figure 15 shows the result of an identical experiment setup to that of section 3.2.3 except for the addition of a 25% raised cosine taper using quinary excitation.

Comparison of figures 11 and 15 reveals that the power of the pulse compression sidelobes have been reduced from -16.34 dB to -29.07 dB, a reduction in power of 12.73 dB, with little effect on the width of the main pulse.

INSERT FIGURE 15 HERE

4 Experimental Observations

Evaluation and comparison of bipolar RTZ and quinary pseudo-chirp excitation is required. To test the processing gain and pulse compression characteristics of each excitation method, an industrial problem has been investigated in the laboratory. The aim of the experiment is to test the pulse compression of various LFM excitation signals after transmission through a channel of low and high attenuation material. The pulse compression and detection of various received signals where direct detection would be impossible or impractical, is also investigated.

Two immersion transducers of central frequency 2.25 MHz with an active element diameter of 0.25 inches were aligned, on axis, with a separation of 0.5 meters between their faces in a pitch catch configuration. The transducers were arranged to be fully submersed in a test liquid or dispersion so as to simulate transducers implanted invasively in the wall of a small industrial vessel. The test tank was first filled with tap water and subsequently with a highly attenuating dispersion. Solid-liquid dispersions formed from fine powders are highly scattering and hence exhibit high attenuation. A solid liquid dispersion of Speswhite© china clay, produced by Imerys, of concentration 5% by weight was produced using tap water. Gravity sedimentation was couteracted by the use of periodic stirring.

Transducer excitation was performed using a custom built pulser as described in section 3.3.2. Six MOSFETs capable of delivering 2 amps of switching current to a single transducers can be operated in simple bipolar RTZ or quinary modes. The MOSFETs were driven by a MOSFET driver circuit. MOSFET firing signals were generated in real time by a FPGA system. Signal capture was performed by a LeCroy WaveRunner 44Xi digital oscilloscope using a 1 MΩ input and no pre-amplification for filtering between the transducer and the oscilloscope input. All data was captured at 200 MS/s without averaging or digital filtering.

4.1.1 Excitation Signals

Four excitation waveforms are used to illustrate the benefits of a windowed quinary LFM excitation over bipolar LFM excitation. Short, 10μs, and long, 100μs, duration waveforms were created using bipolar RTZ excitation and quinary excitation with a 25% raised cosine window. All waveforms shared the same bandwidth of 3 MHz, central frequency of 2.25 MHz and output voltages of $\pm$100 volts. The quinary excitation system utilises additonal $\pm$50 volt output voltage levels.

4.2 Results

All waveforms have been normalised and presented on a decibel scale so SNR can easily be established. Identical pulse compression filters are used for both bipolar and quinary excitation waveforms. The pulse compression filters are not windowed.

4.2.1 Water measurements

Figures 16 and 17 show the improvement in output SNR gained by the use of quinary LFM excitation for signals of 10 μs and 100 μs duration. The input SNR and peak sidelobe power is presented as table 1. For an excitation duration of 10μs the improvement in peak sidelobe power due to quinary excitation is 7.91 dB. Likewise for the 100 μs excitation the improvement is 7.15 dB.

INSERT FIGURE 16 HERE

INSERT FIGURE 17 HERE

INSERT TABLE 1 HERE

4.2.2 Kaolin measurements

Using a single pulse method, the increase in bulk wave attenuation between the two transducers due to the addition of 5% kaolin to the tank was calculated to be 41.6 dB. Figures 18 and 19 show the improvement in output SNR gained by the use of quinary LFM excitation for signals of 10 μs and 100 μs duration. The input SNR and peak sidelobe power is presented as table 2. For an excitation duration of 10μs the improvement in peak sidelobe power due to quinary excitation is 8.18 dB. Likewise for the 100 μs excitation the improvement is 6.22 dB.

INSERT FIGURE 18 HERE

INSERT FIGURE 19 HERE

INSERT TABLE 2 HERE

4.3 Discussion

Quinary pseudo-chirp excitation enables more precise control of ultrasonic transducers output at the extremes of their operating frequencies compared to bipolar pseudo-chip excitation. This is achieved by providing a simple method of tapering the amplitude of the excitation signal. The effect of this amplitude tapering is to reduce broadband pulses at the beginning and end of the transducers response compared to bipolar pseudo-chirp excitation.

The implementation of a quinary system is relatively simple and utilises low cost, reliable MOSFETs and hence is suitable for industrial and medical applications where large discrete output and power amplifier modules may not be desired.

Spread energy systems such as pulse compression LFM systems exhibit a processing gain that enables signals to be detected even when the received SNR is less than 0 dB. Although non-trivial to implement, pulse compression systems can be used to address applications where direct detection is problematic or not feasible.

5 Conclusion

Linear frequency modulated excitation signals and pulse compression filters provide a processing gain by which improved detection of ultrasound signals is possible. These improvements are especially important in applications where highly attenuating channels may be present. We have presented a novel quinary MOSFET based excitation system with basic signal tapering to reduce distortion of the ultrasonic signal. The proposed quinary excitation system is compared to a bipolar pseudo-chirp system and consistently generates lower sidelobes on the output of the pulse compression filters.

This novel, low cost, small form factor, excitation system is especially suited to industrial applications where high excitation powers are required to combat attenuation in long range measurements. Results of industrial scale laboratory based experiments have been demonstrated illustrating the benefits of the quinary excitation system to long range measurements through a highly scattering solid liquid dispersion of kaolin china clay. Quinary LFM excitation consistently generates matched filter outputs with improved SSNR of typically 10 dBs compared to bipolar, pseudo chirp excitation.

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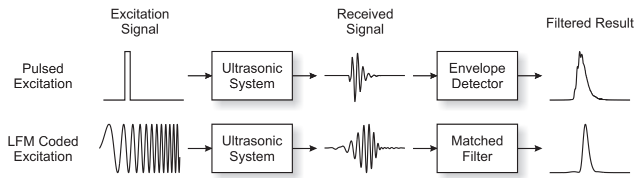

Fig. 1. Comparison between pulsed and LFM coded excitation systems

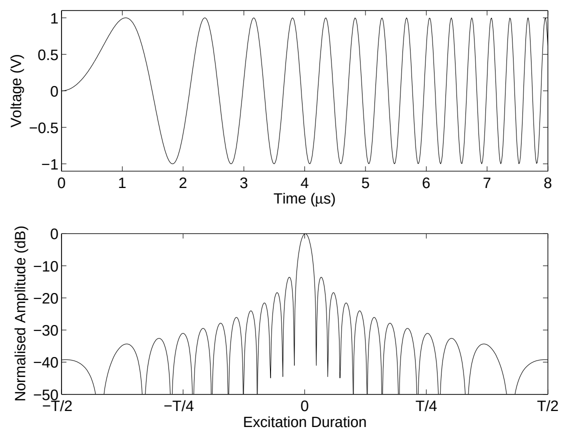

Fig. 2. Analytic LFM waveform (top) and corresponing matched filter output (bottom) illustrating the generation of sidelobes at the reciever

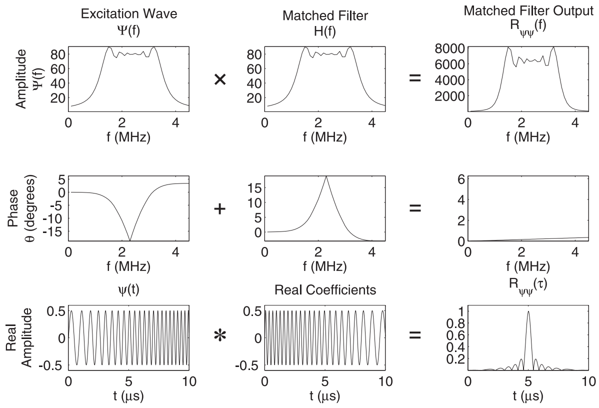

Fig. 3. Diagrammatic explanation of LFM pulse compression in both the frequency and time domain

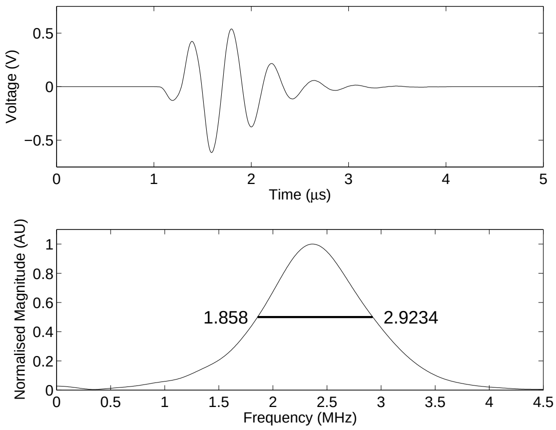

Fig. 4. Impulse response (top) and associated FFT (bottom) for the 2.25 MHz immersion transducers used in simulated and experimental waveforms

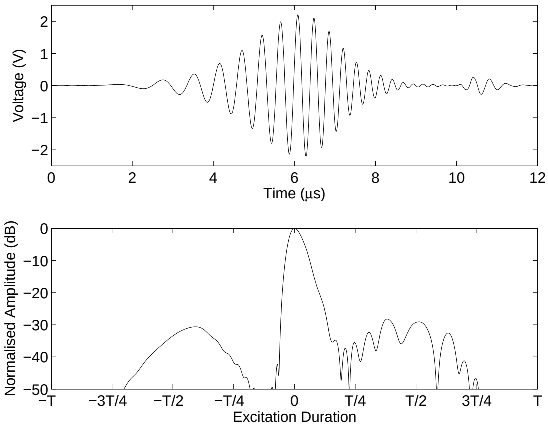

Fig. 5. Effect of the transducer on the received ultrasound waveform (top) and matched filter output (bottom) for LFM excitation

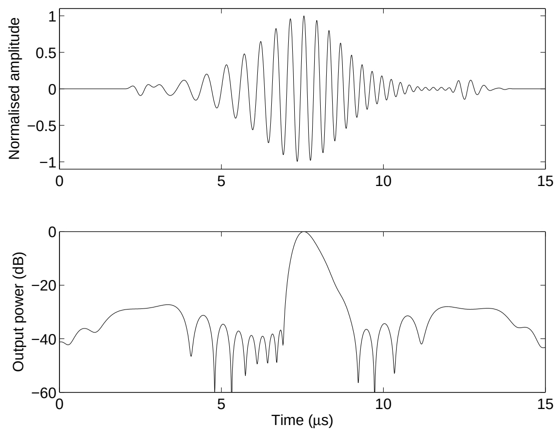

Fig. 6. Simulated received ultrasound waveform (top) and matched filter output (bottom) using LFM excitation without windowing

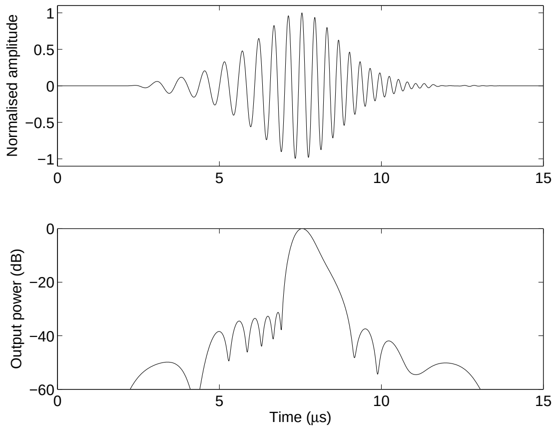

Fig. 7. Simulated received ultrasound waveform (top) and matched filter output (bottom) using LFM excitation witho a 25% raised cosine window

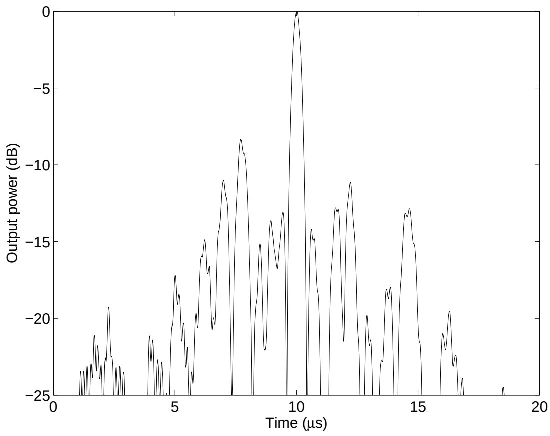

Fig. 8. LFM pulse compression of a input signal with and SNR of -6.43dB

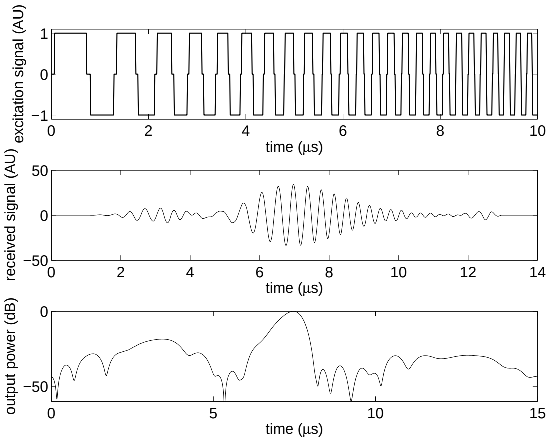

Fig. 9. Simulation of the excitation waveform (top) and received waveform (bottom) for bipolar pseudo-chirp excitation without tapering

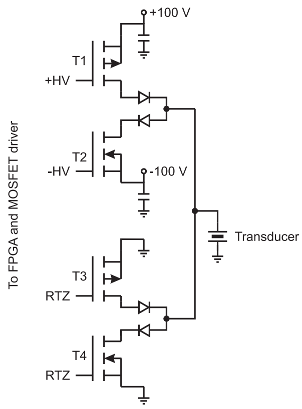

Fig. 10. MOSFET hardware for bipolar return-to-zero (RTZ) excitation

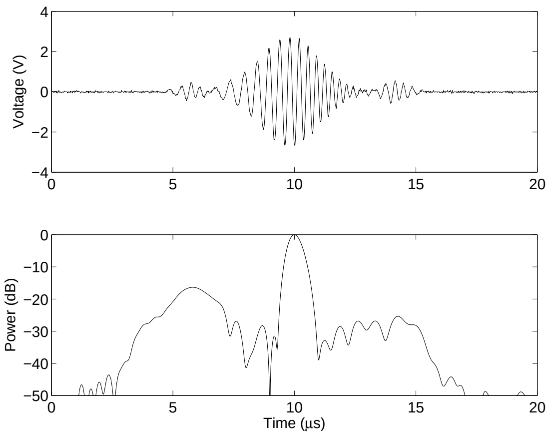

Fig. 11. Experimental received waveforms (top) and matched filter output (bottom) using bipolar pulsed LFM excitation

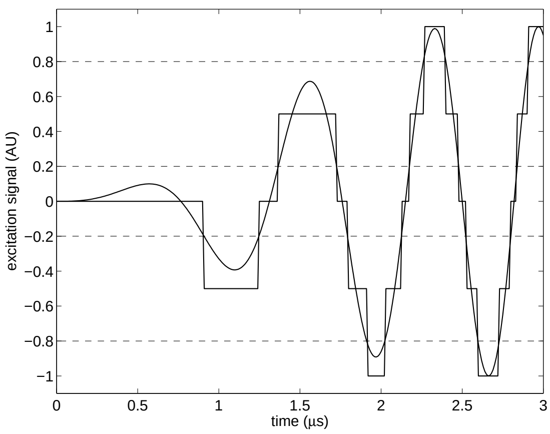

Fig. 12. Comparison of windowing using quinary LFM excitation and analogue excitation

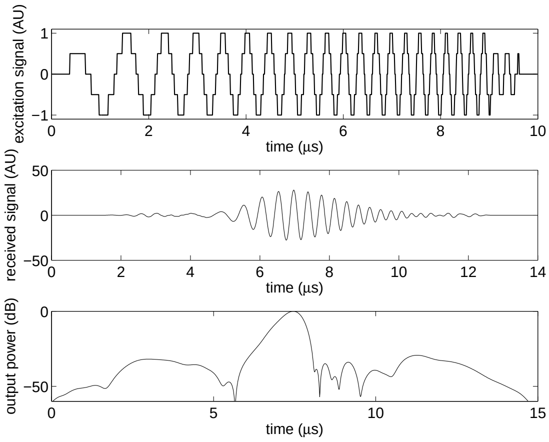

Fig. 13. Simulation of the excitation waveform (top) and received waveform (bottom) for quinary excitation using a 25% raised cosine taper and associated sidelobe suppression

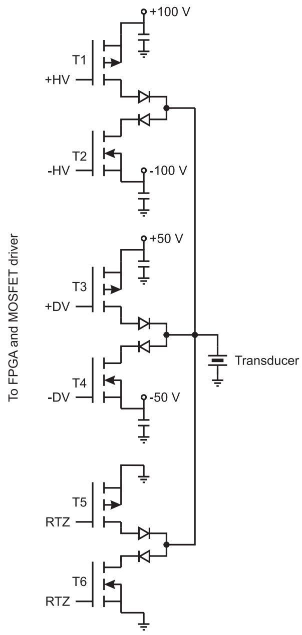

Fig. 14. MOSFET hardware for quinary excitation

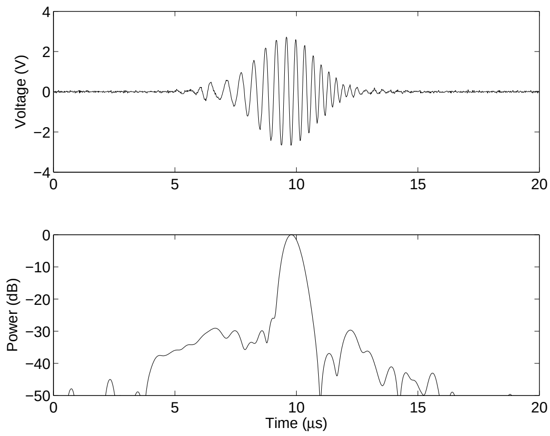

Fig. 15. Experimental received waveforms (top) and matched filter output (bottom) using Quinary pulsed LFM excitation

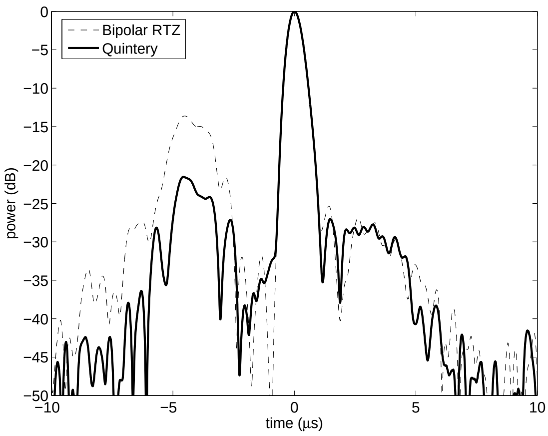

Fig. 16. Comparison between bipolar RTZ and quinary excitation duration of 10μs and bandwidth of 4 MHz in a 0.5 meter tap water channel

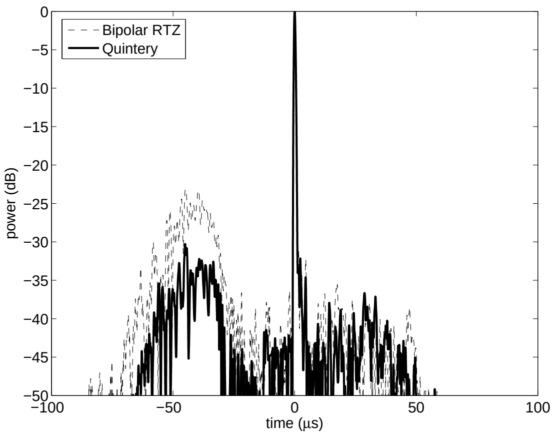

Fig. 17. Comparison between bipolar RTZ and quinary excitation duration of 100μs and bandwidth of 4 MHz in a 0.5 meter tap water channel

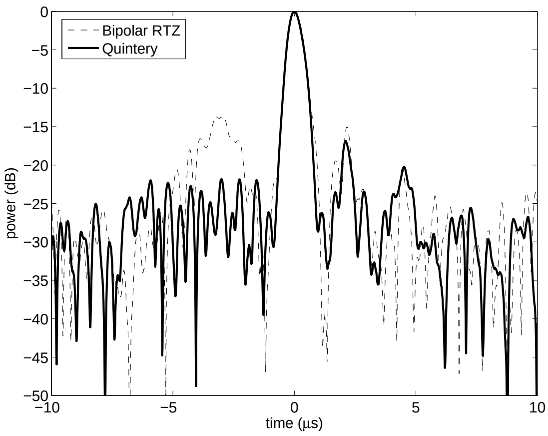

Fig. 18. Comparison between bipolar RTZ and quinary excitation duration of 10μs and bandwidth of 4 MHz in a 0.5 meter 5% kaolin channel

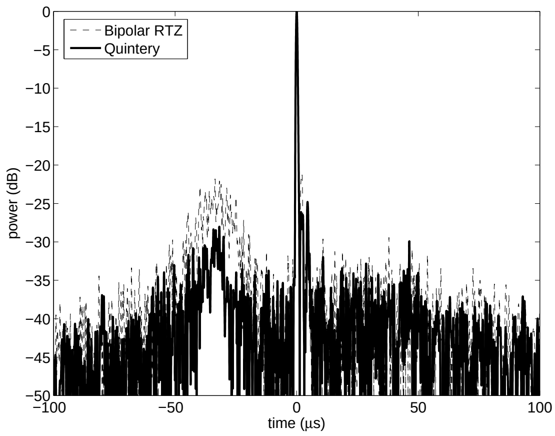

Fig. 19. Comparison between bipolar RTZ and quinary excitation duration of 100μs and bandwidth of 4 MHz in a 0.5 meter 5% kaolin channel

	Exp 1	Exp 2	Exp 3	Exp 4
LFM Duration	10μs	10μs	100μs	100μs
LFM Windowing	0%	25%	0%	25%
Excitation	Bipolar	Quinary	Bipolar	Quinary
Input SNR (dB)	31.31	32.00	33.09	32.57
Output SSNR (dB)	13.62	21.53	23.13	30.28

Table 1

Input SNR and peak sidelobe power of water measurements

	Exp 1	Exp 2	Exp 3	Exp 4
LFM Duration	10μs	10μs	100μs	100μs
LFM Windowing	0%	25%	0%	25%
Excitation	Bipolar	Quinary	Bipolar	Quinary
Input SNR (dB)	4.36	3.33	6.22	7.35
Output SSNR (dB)	13.65	21.83	21.81	28.03

Table 2

Input SNR and peak sidelobe power of kaolin measurements