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A MATLAB-Based Graphical User Interface to Assess Conventional and Chirp-Coded Ultrasonic Excitation

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Abstract

Innovative coded excitation techniques have been proposed to increase the signal-to-noise ratio (SNR) of ultrasound signals, which are significantly attenuated by scattering and absorption. Among the methods applied, the linear-frequency modulation signal, commonly defined as chirp signal, has been studied to provide images with greater depth, even in high attenuation media, maintaining the spatial resolution found in conventional excitation systems. This article presents a graphical user interface (GUI) based on Matlab to simulate short-duration conventional excitation (CE) pulses and long-duration chirp-coded excitation (CCE) pulses. The GUI allows the selection of apodization window, center frequency, and pulse duration parameters. In addition, it is possible to configure the bandwidth of the chirp signal. Pulse evaluations were performed with a central frequency of 1.6 MHz, using three cycles for CE and a duration of 5, 10, and 20 μs for CCE with a bandwidth of ±200 kHz, ±400 kHz, and ±1 MHz in a phantom simulated with ten targets. The echo signals for the CCE were processed using a matched filter to evaluate the spatial resolution and attenuation. Simulation results demonstrate the flexibility and performance of the proposed GUI for ultrasound excitation studies. The evaluation of CCE with a frequency of 1.6 MHz ± 1 MHz and matched filter improved spatial resolution by 86%. In contrast, a maximum increase in attenuation of the processed signal of 33% was observed.

Keywords: Ultrasound; conventional excitation; chirp-coded excitation; match filter; signal processing

Introduction

Ultrasound imaging is one of the most widespread modalities in various applications and clinical examinations in the medical field. Among the advantages of ultrasound, it can be underlined the ability to generate images in real-time, its non-ionizing nature, being a non-invasive method, and having a relatively low cost compared to other medical imaging diagnoses [13, 15, 3].

The spatial resolution and penetration depth are the main parameters to determine the quality of the ultrasound image [4]. There is an improvement in the spatial resolution due to the high frequencies of ultrasonic emission with conventional excitation (CE) of short duration and Gaussian profile, typically up to 20 MHz. However, the attenuation is strongly frequency-dependent and, consequently, imposes limitations on the penetration capacity of the acoustic wave [14]. An alternative to overcome this obstacle is to increase the power of acoustic emission, increasing the amplitude or duration of the excitation pulse. However, increasing the excitation signal amplitude increases the instantaneous acoustic power, a parameter that is limited to pre-established values by regulatory agencies [9]. An ultrasound-encoded excitation method, which causes an increase in the transmitted pulse, was proposed by O'Donnell to overcome that limitation in 1992 [10].

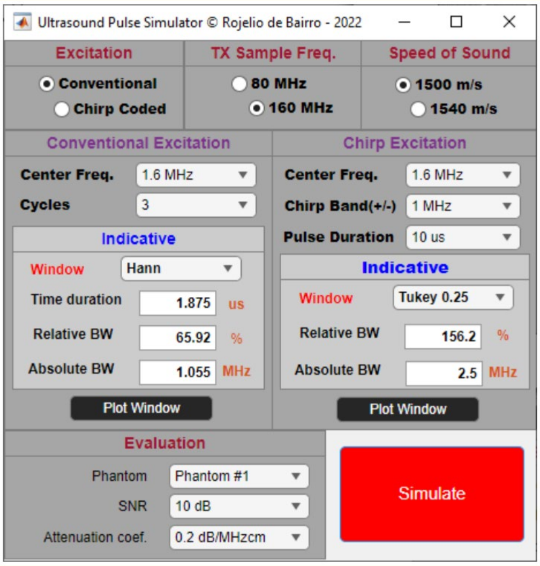
The use of coded excitation techniques makes it possible to lengthen the transmitted pulse with modulations temporarily, subsequently compressing the output (reception), usually through a matched or mismatched filter. Coded chirp excitation (CCE) ultrasound signals are used for this function. The advantages of using coded signals are an increase in penetration depth and an increase in the signal-to-noise ratio (SNR). A higher SNR allows images of structures located deeper within the human body to be captured with better resolution [7, 8].

For the development and evaluation of innovative transmission techniques, it is necessary to have access to excitation control parameters that, usually, are not fully available in commercial ultrasound equipment. Thus, the development of computational simulation tools, and open and flexible ultrasound platforms for research, with the ability to generate coded ultrasound pulses, have been proposed [7, 8, 5, 12, 11]. As an example, Medeiros et al. [6] presented a flexible Matlab-based interface to simulate complex analog waveforms with fixed pulse duration.

This article presents a new graphical user interface (GUI) with the App Designer program, which is part of Matlab, to simulate CE and CCE pulses of short and long duration. The methods and results of generated signals in a simulated phantom are presented. In the case of CCE, applying a matched filter for signal optimization was evaluated.

Materials and Methods

The computational tool used in this work to develop the GUI was the software Matlab® Release 2022a (MathWorks Inc, USA). Fig. 1 shows the interface developed for simulating CE and CCE pulses. Pulses' interaction with the medium - in this case, a computational phantom - was also evaluated using the GUI.


Ultrasound Pulse Simulator © Rojelio de Bairro - 2022

Excitation: ● Conventional ○ Chirp Coded
TX Sample Freq.: ○ 80 MHz ● 160 MHz
Speed of Sound: ● 1500 m/s ○ 1540 m/s

Conventional Excitation
Center Freq.: 1.6 MHz
Cycles: 3
Indicative
Window: Hann
Time duration: 1.875 us
Relative BW: 65.92 %
Absolute BW: 1.055 MHz

Chirp Excitation
Center Freq.: 1.6 MHz
Chirp Band(+/-): 1 MHz
Pulse Duration: 10 us
Indicative
Window: Tukey 0.25
Relative BW: 156.2 %
Absolute BW: 2.5 MHz

Evaluation
Phantom: Phantom #1
SNR: 10 dB
Attenuation coef.: 0.2 dB/MHzcm

Figure 1: Graphical user interface proposed for ultrasonic excitation research.

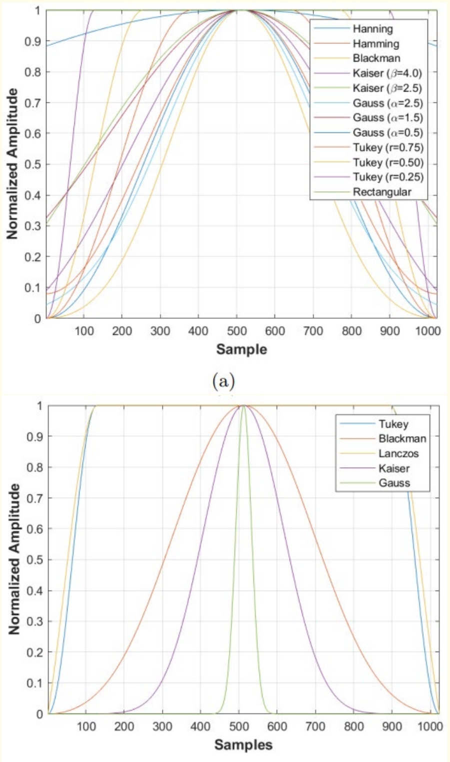
For CE evaluation, it is possible to configure the central frequency (f_c), the number of cycles, and the apodization window. The CCE configuration has the parameters for bandwidth and pulse duration. The linear frequency chirp is calculated by using (1), where f_0 and ϕ_0 are the starting frequency and the initial phase, respectively, at time t=0, f_1 is the final frequency, and T is the time it takes to sweep from f_0 to f_1.

$$x(t) = sin\left[\phi_0 + 2\pi\left(\frac{f_1 - f_0}{2T} \cdot t^2 + f_0 t\right)\right] \tag{1}$$

$$BW_{rel} = \frac{BW_{abs}}{f_c} \cdot 100 \tag{2}$$

The spectrum's absolute (BW_{abs}) and relative (BW_{rel}) bandwidths in the generated signal frequency are calculated in both cases. The BW_{abs} is obtained through the Fast Fourier Transform (FFT) at -6 dB, and the BW_{rel} is calculated according to (2).

For pulse shape definition, windowing functions were included for both excitation modes. Fig. 2a and Fig. 2b show the window options implemented in the GUI for CE and CCE, respectively. The x-scale indicates the number of samples used in both simulations for illustrative purposes. This number depends on the parameters selected in the GUI.



(a)

(b)

Figure 2: Windowing options for (a) CE and (b) CCE.

The available parameter configuration options are shown in Table 1. However, other options can be easily implemented.

Item	Options
Speed of sound [m/s]	1500 and 1540
Sampling frequency [MHz]	80 and 160
Central frequency [MHz]	0.5, 1.6 and 5.0
Chirp signal bandwidth [MHz]	±0.2, ±0.4, ±1.0 and ±2.0
Chirp pulse duration [µs]	5, 10 and 20
Number of cycles	Between 3 and 10
Phantom selection for simulation	Pre-computed phantoms
Gaussian white noise [dB]	0 (max.) to 30 (min.)
Medium attenuation coefficient	0.1 to 2.0 dB/MHz.cm

*The phantom must be generated by script before the simulation.

Table 1: GUI Configuration Parameters.

After configuring all the excitation parameters, the simulation is performed by clicking the Simulate button. Then, the impulse response, its frequency response, the convolution of the signal with the simulated phantom, and the logarithmic compression of the final signal, presented in the next section, are generated. The phantom shown in Fig. 3 was modeled in a one-dimensional structure with ten scatters (A1 to A10) spaced 10 mm apart, as described in [2].

For evaluation of the GUI, CE tests were performed with a central frequency of 1.6 MHz, duration of 3 pulses, and Hanning windowing. The CCE was evaluated with a central frequency of 1.6 MHz, durations of 5, 10, and 20 µs, band-width of ±200 kHz, ±400 kHz, and ±1 MHz, and Tukey windowing (25%). The sampling frequency was set at 160 MHz, and the sound propagation speed was set at 1500 m/s.

This work results in a quality optimization of the ultrasound signal with the CCE. Waveforms were processed using a matched filter. This compression technique allows maximizing the SNR in the presence of white Gaussian noise to improve the quality of the ultrasonic image. After acquiring the radiofrequency (RF) echo, the time inversion of the impulse response of the CCE pulse is performed to generate the matched filter. This signal is convolved with the backscattered signal to generate the compressed signal. White noise with attenuation of 10 dB was added to the convolved signal to verify the attenuation and axial resolution behavior.

Results

This section evaluates excitation/compression mechanisms' effects on ultrasonic signals. Furthermore, a comparison of the magnitude of the main lobes and axial resolution of the ten targets at -6 dB of the generated signals by CE and

CCE with matched filter is presented. The tests were performed considering the attenuation of the medium of 0.2 dB/MHz.cm.

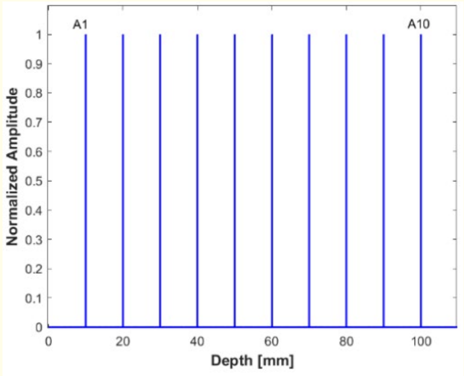


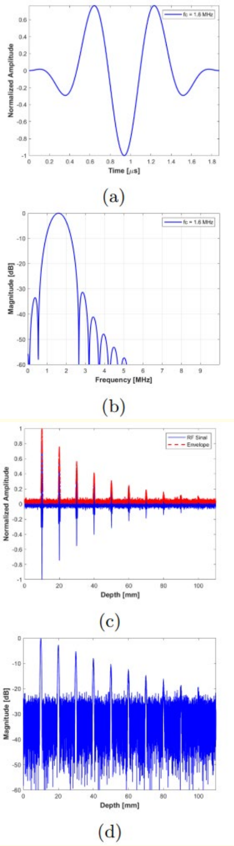
Figure 3: Computer phantom with ten targets.

Conventional Excitation

The CE pulse is shown in Fig. 4a. For this signal, the BW_{abs} and the BW_{rel} were equal to 1.055 MHz and 65.92%, respectively, obtained through the frequency spectrum shown in Fig. 4b. Fig. 4c shows the result of the convolution of the CE pulse with the computational phantom to simulate the backscattered signals. In addition to the resulting echo, the red dashed curve is the signal envelope obtained by the absolute value of the Hilbert Transform [1]. Logarithmic compression is applied to the envelope to better visualize the signal with a dynamic range of -60 dB, as shown in Fig. 4d. This signal has a significant amount of noise that prevents the definition of the deepest targets, precisely, A9 and A10.

Coded Chirp Excitation

Fig. 5a shows the CCE signal with a frequency of 1.6 MHz ± 1 MHz and a duration of 10 µs due to the applied windowing. BW_{abs} and BW_{rel}, equal to 2.5 MHz and 156.3%, respectively, were obtained from the frequency spectrum of the chirp signal in Fig. 5b. Fig. 5c shows the result of the convolution of the CCE pulse with the computational phantom and the respective envelope. Fig. 5d shows the sign after logarithmic compression. In this case, the target axial resolution is compromised as a function of the width of the long-duration CCE pulses.



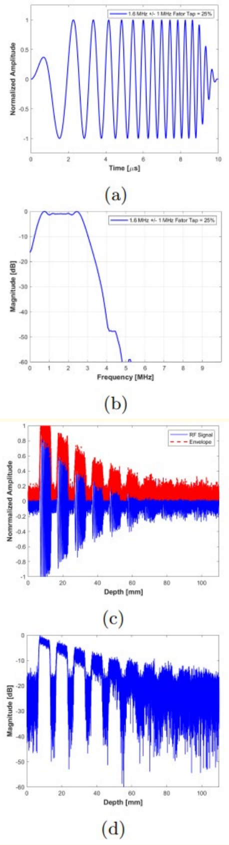
(a)

(b)

(c)

(d)

Figure 4: (a) CE pulse. (b) Pulse frequency spectrum. (c) Simulation of backscattered signals. (d) Logarithmic compression of the echo signal.



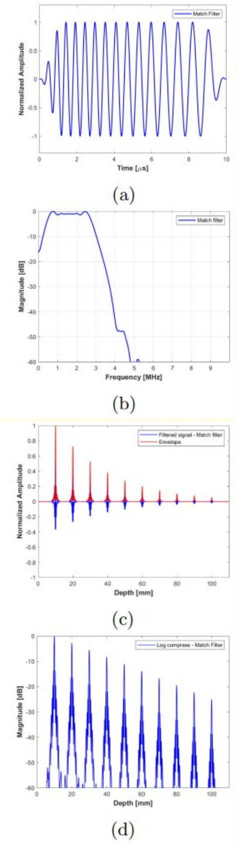
(a)

(b)

(c)

(d)

Figure 5: (a) CCE pulse. (b) Pulse frequency spectrum. (c) Simulation of backscattered signals. (d) Logarithmic compression of the echo signal.



(a)

(b)

(c)

(d)

Figure 6: (a) Matched filter. (b) Filter frequency spectrum. (c) CCE pulse compressed by the matched filter. (d) Logarithmic compression of the resulting signal.

Coded Chirp Excitation with Pulse Compression

The time inversion of the CCE impulse response, corresponding to the matched filter, and its frequency spectrum are shown in Fig. 6a and Fig. 6b, respectively. The convolution result with the backscattered signal shown in Fig. 5c with the matched filter of Fig. 6a is shown in 6c. Compared to Fig. 4d and Fig. 6d, applying the matched filter improves the SNR and axial resolution of the ten targets. However, that compression caused secondary lobes that could indicate false artifacts. These lobes can be minimized in future works by applying mismatched filters [7, 8].

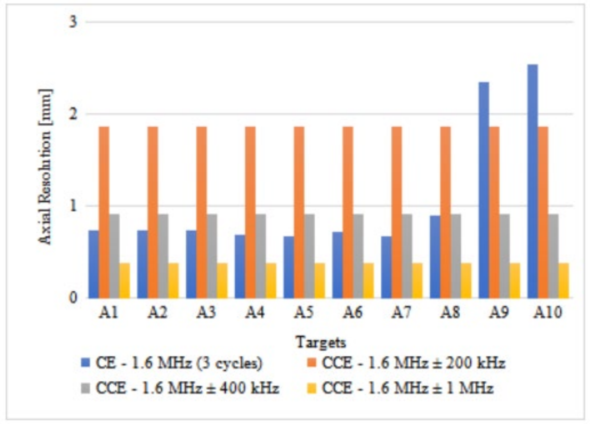


Figure 7: Comparison of the axial resolution of CE and CCE signals in the phantom.

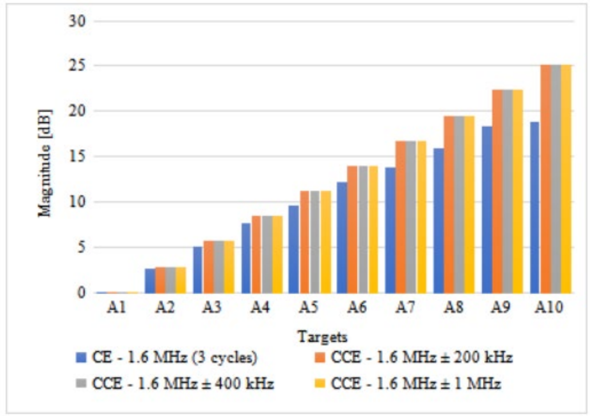


Figure 8: Comparison of CE and CCE signal attenuation in the phantom.

In order to quantitatively compare CE and CCE with matched filter, Fig. 7 shows the results of the evaluation of the axial resolution in the phantom. As expected, the axial resolution of the CE gets worse with depth, especially on the A9 and A10 targets. This behavior did not occur in the CCE, which remained stable. The mean value of the axial resolution of the CCE for the frequency of 1.6 MHz and bandwidths of ±200 kHz, ±400 kHz, and ±1 MHz was equal to 1.842, 0.900, and 0.361 mm, respectively, with zero standard deviation in all the cases. Considering targets A9 and A10, the best axial resolution of CCE with matched filter occurred with ±1 MHz band and was equal to 85 and 86%, respectively.

Fig. 8 presents the evaluation of the signal attenuation, and the target A1 has an attenuation of 0 dB. CE presented better results for all targets, with a maximum difference of 33% in target A10. On the other hand, the attenuation of the CCE was the same for each target in the different bandwidths. Thus, there is a cost-benefit relationship between the application of the techniques since processing the encoded chirp signal requires a more significant computational effort.

Conclusion

This work presented a flexible GUI for simulating short and long excitation pulses. This computational tool can be used in the research of new techniques for optimizing the quality of images generated by ultrasound using CE and CCE. The GUI is easy to use, and customizations can be performed according to scientific research needs. The presented study shows that the optimization of excitation parameters plays a relevant role in improving the SNR using chirp-coded pulses in deeper regions. This work is a continuation of the research started in [6], in which the GUIDE tool from Matlab was used. In this work, the APP Designer software enabled a better use of new layout applications and integration with digital signal processing tools that will be evaluated in future research.

Conflict of Interest

The authors declare that they have no conflict of interest.

Acknowledgements

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