A Novel Hybrid Pulse Excitation - Coded Excitation Scheme to Improve the Signal to Noise Ratio in Ultrasound Imaging

N. ASADI, S. K. SETAREHDAN, and H. SOLTANIANZADEH
Electrical and Computer Engineering Department, Faculty of Engineering
University of Tehran
P.O. Box: 14395/1355
IRAN
n_asadi@lycos.com

Abstract: - While simple pulse excitation of the ultrasound transducer is conventionally used in ultrasound imaging, the coded excitation scheme of the transducer was proposed recently to improve the image quality and penetration depth. In this article, a novel combined "pulse excitation - coded excitation" approach is presented. The most distinctive feature of the proposed approach, in comparison to the previously reported coded excitation methods, is the fact that the excitation codes in our approach are adaptively generated for each scan line using the information obtained by a simple pulse excitation prior to the coded excitation of the transducer. Therefore, the interaction between the tissue and the ultrasound beam travelling through it is the main source of information, which is used to generate the codes in the new scheme.
A systematic method for generating the ultrasound signals due to the coded excitation of the transducer is explained in this paper. Moreover, the improvements in the SNR are quantitatively compared to the previous methods.

Key-Words: Sonography, Ultrasound imaging, Coded excitation, Matched filter, Chirp, Nonlinear FM signal

1 Introduction

As an important medical diagnostic tool, ultrasound imaging has been extensively used over the past couple of decades. Although the quality of an ultrasound image is not as good as those generated by Magnetic Resonance Imaging (MRI) or Computed Tomography (CT), however, its numerous advantages like using no ionising radiations, being non-invasive, portable, low-cost, versatile, and generating real time images have made it the first choice of physicians in most cases. Therefore any new idea to improve the ultrasound image quality has been seriously taken into consideration. Previous methods to improve the ultrasound image quality like increasing the frequency of the ultrasound wave itself and/or compounding information in the spatial and frequency domains have usually linked with such problems as the reduction in the penetration depth or reduction in the frame rate [1].

Several new methods for improving the quality of the ultrasound image and increasing the penetration depth are reported recently, which are mostly based on delivering more ultrasound energy into the tissue. These methods are generally referred to as the "coded excitation" of the ultrasound transducer. However, due to the limitation in the peak ultrasound power, which is set to avoid any tissue damage and cavitations, using a long ultrasound burst with a small amplitude instead of a short ultrasound burst with a large amplitude is considered as the only possible strategy. On the other hand, it is obvious that elongating the excitation pulse in the time domain will cause a reduction in the axial resolution. In order to overcome this problem, post processing of the recorded echo ultrasound signal is necessary.

One of the common techniques used for this purpose is matched filtering, which is initially used in radar and sonar systems. Apart from additional hardware complexity required in the excitation circuit, a main reason for its limited utilisation in the ultrasound field is the frequency dependent attenuation of the ultrasound signal when it travels within the tissue. The presence of the speckle noise in ultrasound images must also be considered as another reason.

As a pioneer, O'Donnell [2] developed a coded excitation based ultrasonic imaging system and showed that with this method the maximum achievable improvement in the SNR is restricted to 20dB. However, for an acceptable axial resolution it is necessary to reduce this limit to 10 to 15dB [2]. One of the most common coded excitation signals used in ultrasound imaging is the Chirp or linear FM signal. This is because of its desired characteristics such as producing small side-lobes at the output of the matched filter, allowing an easy control of the bandwidth of the signal, and a better stability with respect the ultrasound attenuation in tissue.

Pollakowski [6] had suggested the use of a non-linear FM signal such that its frequency components have the perfect match with the frequency response of the ultrasound transducer. This and other similar studies had considered the inherent limits of the coded excitation scheme, like necessarily using long excitation pulses and the naturally limited bandwidth of the ultrasounds transducer.

In this paper, we aim to develop such exciting codes that the frequency components of the resulting ultrasound signal to have as close match as possible with the frequency response of the path inside the tissue were the signal travels. The frequency response of the pulse travelling route within the tissue is initially obtained using the regular pulse excitation of the ultrasound probe. Then, based on the information obtained about the travelling route, a new coded excitation signal is generated for the route under consideration. It is obvious that for any scan line a particular code will be generated and used.

The rest of the paper describes this novel idea, the process of generating the special codes for each scan line and the performance analysis of the proposed method in more details.

2 Description of the proposed method

A linear FM signal (Chirp) is defined as follows:

$$s(t) = a.\cos[j2\pi(f_0 t + \frac{B}{2T}t^2)]; \qquad \frac{-T}{2} \le t \le \frac{T}{2} \tag{1}$$

where f_0 is the center frequency, T is the signal duration and B is the bandwidth of the signal. Instantaneous frequency of this signal is given by:

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

which is a linear function of time and shows the spectral band that includes most energy of the signal at time t. For generating a coded excitation using the Chirp signal, the transducer is excited with this signal and the resulting ultrasound burst applied to the tissue. In practice, the combination of the ultrasound transducer and the tissue can be considered as a single system with a transfer function *g(t)*. The collected ultrasound RF echo, which is the response of the combined transducer-tissue system to the Chirp excitation, is then feed to a matched filter.

By definition, the impulse response of the matched filter that maximizes the SNR of the input signal *s(t)* is as follows:

$$h(t) = s(T - t) \tag{3}$$

The frequency domain representation of this function is as follows:

$$H(f) = e^{-j2\pi fT} S^*(f) \tag{4}$$

As mentioned earlier, the main idea in the proposed algorithm is to make the spectrum of the excitation signal as similar as possible to the transfer function of the combined transducer-tissue system *G(f)*. This will obviously improve the SNR of the ultrasound echo signal. One practical point at this stage is that since the transfer function of the matched filter is proportional to the spectrum of this signal, if the excitation signal is chosen so that *S(f)=G(f)*, then this function appears in the match filter twice (power of 2 of the spectrum of the signal). To avoid this problem, the excitation signal is usually applied in the form of $S(f) = \sqrt{G(f)}$. A similar selection is usually done in designing transmitters for the Pulse Amplitude Modulation (PAM) systems, which is shown to be optimal in term of the SNR [7].

Now, we would like to generate a nonlinear excitation FM signal based on the spectrum of the Chirp signal *S(f)*. Here only the instantaneous frequency of the nonlinear FM signal is changed so that in frequencies where signal spectrum has higher amplitude frequency is swept slowly. To drive the equation of the instantaneous frequency of the nonlinear FM signal, we choose to use the following approximation between the group delay function and the amplitude of the spectrum:

$$-\frac{d\tau_g(f)}{df} = K.|S(f)|^2 \tag{5}$$

where K is a constant. Using this equation group delay for different frequencies can be calculated as follows:

$$\tau_g(f) = \int_{f_1}^{f} C_1.|S(f)|^2 df + C_2 = \int_{f_1}^{f} C_1.|G(f)| df + C_2 \tag{6}$$

where C_1 and C_2 are the integration constants and they are chosen so that $\tau_g(f_1) = 0$ and $\tau_g(f_2) = T$. In this equation f_1 and f_2 are the lower and higher boundaries for the frequency sweep. In the next step instantaneous frequency $f(\tau_g)$ can be computed as a function of group delay by calculating the inverse function $\tau_g(f)$. Since time spacing in this function is not regular, therefore calculating the inverse function needs interpolation. As a result, the nonlinear FM signal is generated for each scan line of the image separately and used as an excitation signal for that scan-line.

3 Simulation and results

In order to assess the proposed method the Field II software [8] is used, which comprises several MATLAB m-files. Field II calculates acoustic fields and the resulting pressure wave allowing defining the desired ultrasound transducer. In this software the standard Rayleigh equation has been used to compute the acoustic pressure field, which is a description of the Huyghen's principle. The simulated synthetic phantom consists of 8 point scatterers with a distance of 10mm in between them. The central frequency of the transducer for which the frequency response is shown in Figure 1 is set to 4MHz. A sampling frequency of 100 MHz is chosen.

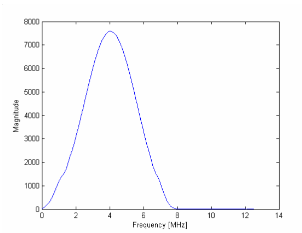

Figure 1: Frequency response of the simulated transducer

In continue, the three different kind of excitation signals namely the pulse excitation, the Chirp excitation and the proposed nonlinear FM signal were applied to desired transducer and phantom. The results are compared to each other in Figures 2 to 4. Figure 2 (right) demonstrates the pulse excitation for which the resulting RF echoes are shown in Figure 2 (left). The *dynamic focusing* technique is used in the receive mode.

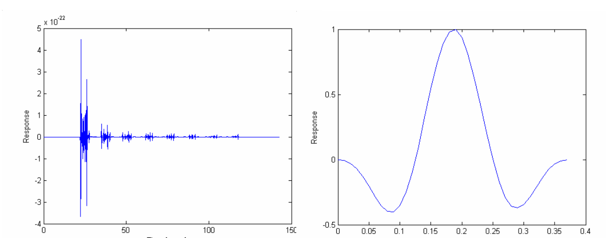

Figure 2: The resulting signal for pulse excitation (right) and the corresponding echoes (left)

For the Chirp excitation, the frequency sweep was chosen according to the bandpass characteristics of the transducer. Moreover, to reduce the sidelobes of the resulting ultrasound burst amplitude tapering is performed by means of a Chebyshev window with a duration of one-tenth of the duration of the Chirp signal at the beginning and end of the signal as shown in Fig. 3 (up right).

This windowing procedure reduces also the Fresnel ripples in the spectrum of the chirp [5]. Applying this signal to the matched filter produces the result shown in Figure 3 (bottom right). As it can be seen from Figures 2 and 3 the resulting signal from pulse and Chirp excitations after passing through the matched filter are very similar except that the resulting signal from the Chirp excitation has very larger amplitudes. It is also noticeable that, as it was expected the spectrum of the signal in Figure 2 (bottom right) is similar to the frequency response of the transducer which is shown in Figure 1.

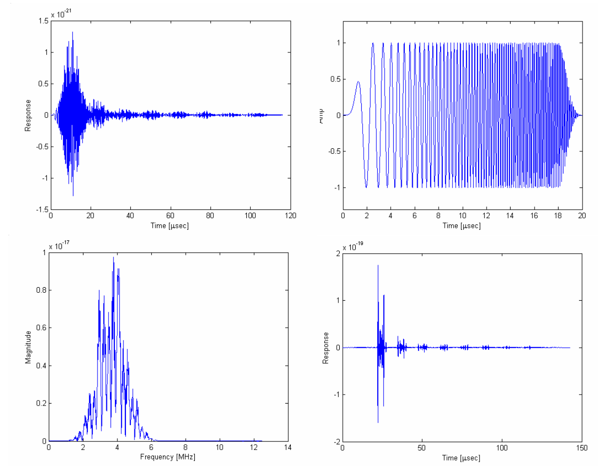

Figure 3: Chirp excitation. Tapered FM signal (up right) and resulting echoes (up left). Echoes after matched filtering (bottom right) and its frequency response (bottom left).

Finally, Figure 4 (up) demonstrates the nonlinear FM signal and its spectrum. This signal is obtained by performing the square root of the RF spectrum shown in Figure 2 as explained before. As it can be seen the amplitude and duration of this signal is similar to those of the Chirp signal, however, it has different energy distribution pattern. Applying the tapering window to this signal produces the final excitation signal, which is shown together with its spectrum in Figure 4 (center). The resulting RF echo after applying this coded excitation signal to the predefined phantom is shown in Figure 4 (bottom). It can be seen that the amplitude of the resulting echoes are increased compared to both of the two previous cases (pulse and Chirp excitation). As a remarkable achievement, the detecting threshold, which is commonly used in ultrasound signal conditioning stage, can be chosen larger, resulting more suppression of the noise in the ultrasound signal.

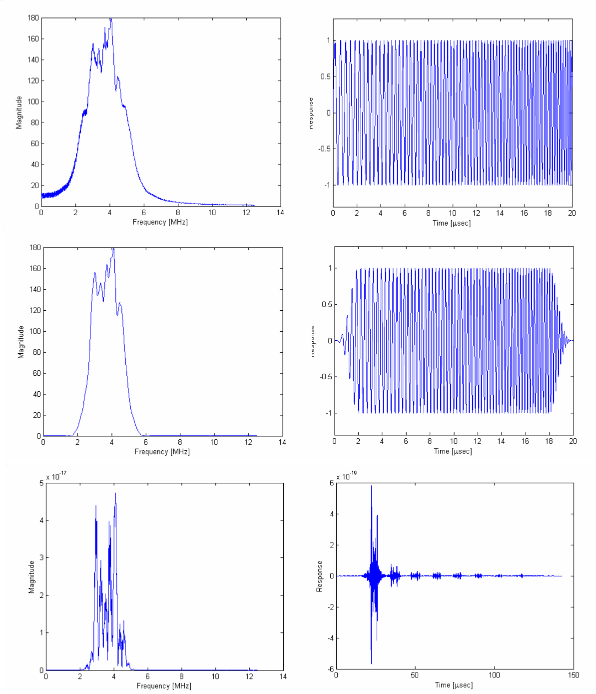

Figure 4: Nonlinear FM excitation. Nonlinear FM signal and its spectrum (up). The same signal and its spectrum after tapering (center). Resulting echoes after matched filtering and its frequency response (bottom).

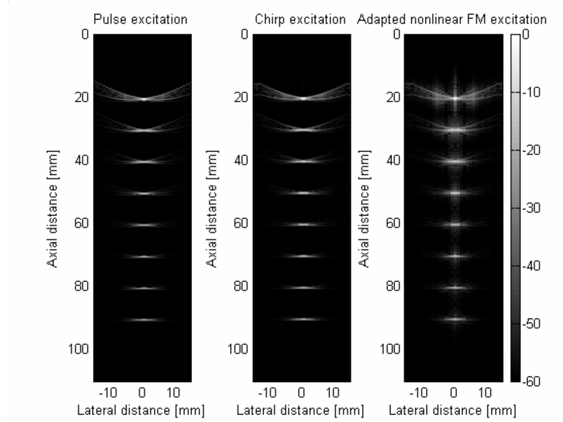

Figure 5: Ultrasound images obtained using different excitation signals

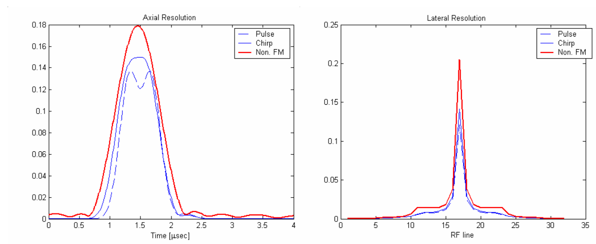

Figure 6: The lateral resolution (right) and the axial resolution (left) for the three different excitations

At this stage we construct the whole ultrasound image of the phantom using each one of the three above methods. As a regular method in generating the ultrasound image, it is necessary to compute the envelope of the RF echo signals, scan-line conversion, logarithmic compression and the grey scale demonstration of the image. The resulting images are shown in Figure 5 for the three methods. In generating these images, the linear array imaging with 32 scan-lines and a dynamic range of 60dB are considered. The resulting axial and lateral resolutions in the three methods are also compared in Figure 6, by comparing the normalized envelope of the three RF signals. Since the phantom is chosen to include only a number of point scatterers, the width of the envelope signals show the resolution in different directions. It can be seen that the amplitude level of 0.1499 for the Chirp excitation increased to a value of 0.1788 for the proposed nonlinear FM excitation, which is equivalent to a 3.06dB improvement in the SNR.

4 Conclusion and suggestion

A novel method for constructing coded excitation signals in ultrasound imaging was presented. The goal in generating the coded excitation signals in this work was to generate such excitation signals that the frequency components of the resulting ultrasound signal to have as close match as possible with the frequency response of the path inside the tissue were the signal travels. The frequency response of the pulse travelling route within the tissue was initially obtained using the regular pulse excitation of the ultrasound probe. Then, based on the information obtained about the travelling route, the new coded excitation signal was generated for the route under consideration.

The simulated data from the well-known programming software of Filed II were used to show that the new coded excitation signal increases the amplitude of the RF echoes and therefore the SNR of the resulting ultrasound images using the same amplitude and duration as the commonly used Chirp signals.

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