IMPROVING SNR AND BANDWIDTH OF SHEAR-WAVE DISPLACEMENTS VIA MODULATED FORCE EXCITATION

Enrique González-Mateo[1*], Francisco Camarena[1], Noé Jiménez[1]

[1]Instituto de Instrumentación para Imagen Molecular, CSIC - Universitat Politècnica de València, España

ABSTRACT

Ultrasound shear wave elastography aims to induce shear waves in soft tissues through dynamic stress and assess their elasticity by measuring wave velocity. However, limitations in ultrasound imaging, including shadowing, reverberation, and depth-dependent attenuation, often result in low signal-to-noise ratio (SNR) signals, which pose challenges for capturing shear waves. This study proposes a method to overcome these limitations and obtain reliable shear wave information. The method involves using long modulated force excitations to generate tissue motion and demodulating the resulting displacements from pulse code excitations. This demodulation separates individual impulse responses, allowing for the recovery of the original pulse shape and enhancing displacement amplitude and SNR. Simulations using soft tissue elastic pseudospectral time domain techniques prove that the method, employing coded excitations like maximum-length sequences and frequency sine sweep, increases the time-bandwidth product and achieves significant SNR improvement through pulse compression. By improving the quality of displacement data and reducing noise, the method enhances the robustness of algorithms used to estimate shear wave propagation speed, minimizing the potential for biased results.

Keywords— *Shear waves, Elastography, Soft tissue, Signal to noise ratio, Pulse compression.*

1. INTRODUCTION

Elastography is a medical imaging technique that is increasingly being employed in medicine. In contrast to traditional anatomical imaging, elastographic imaging supplies functional information about the elasticity of soft tissue. The combination of anatomical and elastographic imaging can provide valuable insights for detecting pathologies such as fibrosis or prostate cancer [1], [2].

The mechanism for measuring the elastic properties of tissue involves three phases: (1) The first phase involves stimulating the tissue to generate shear waves, which move at a much lower speed (1.5-10 m/s) than the propagation speed of soft tissue (1540 m/s). There are two primary methods for exciting the tissue: passive methods, such as external exciters, and dynamic methods, such as acoustic radiation force (ARF). (2) The second phase involves capturing the displacements of the shear waves generated during excitation. Various medical imaging technologies, such as magnetic resonance imaging, ultrasound, or optical methods, can be used for this purpose. (3) The final phase involves reconstructing the elasticity map based on the displacements. Through this process, we can figure out the velocity of shear waves propagating through the tissue and calculate the mechanical properties of the tissue, which, in purely elastic tissue, are related to Young's modulus,

$$E = 3c_s^2\rho_0 \tag{1}$$

where is the shear velocity and ρ_0 is the density of the medium. Elastographic image formation methods rely heavily on the quality of shear wave displacements, which can be compromised by factors such as reflections, medium attenuation, and shear wave attenuation.

This paper proposes a novel shear wave generation method based on long ARF pulses modulated with random sequences (MLS). MLS is a pseudo-random binary sequence with a period of $2N - 1$ generated by a linear recursion of degree N [3]. Such signals are commonly used to measure the impulse responses of linear time-invariant systems in acoustic and audio systems due to their high signal-to-noise ratio (SNR) and robustness against impulsive or non-stationary disturbances. The goal is to enhance the SNR by calculating the impulse response of the medium using pulse compression techniques initially used in general with radar applications [4].

[*]***Contact author***: *engonmar@upv.es*

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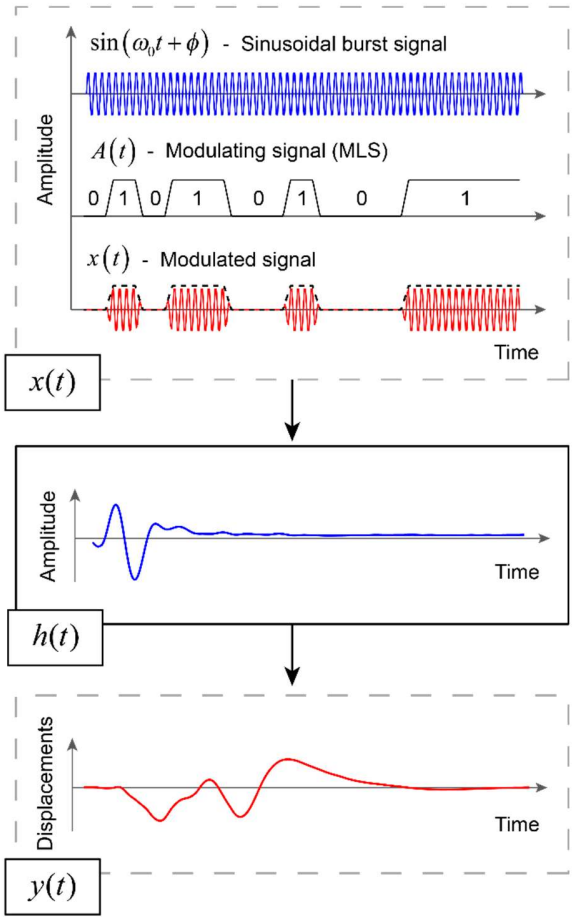


Figure 1. Graphic diagram of the linear time-invariant system. The upper block refers to the system input x(t), which results from modulating an ARF signal with an MLS signal. The middle block is the impulse response of the medium h(t). The lower block refers to the system output in terms of displacement y(t) generated by exciting the medium with x(t).

This paper presents the fundamentals of the method and the results obtained from pseudo-spectral time simulations used for method validation.

2. METHODS

Figure 1 illustrates the operational framework of the proposed method. The technique relies on the use of broadband excitation signals, in this case, pseudorandom, to obtain the impulse response of the medium, assuming it behaves as a linear time-invariant (LTI) system.

The first step involves generating a pseudorandom MLS sequence of degree N [5]. Since the SNR gain depends on the code length and is proportional to $10 \cdot log_{10}(N)$, it is desirable to create long binary codes that are also invertible and

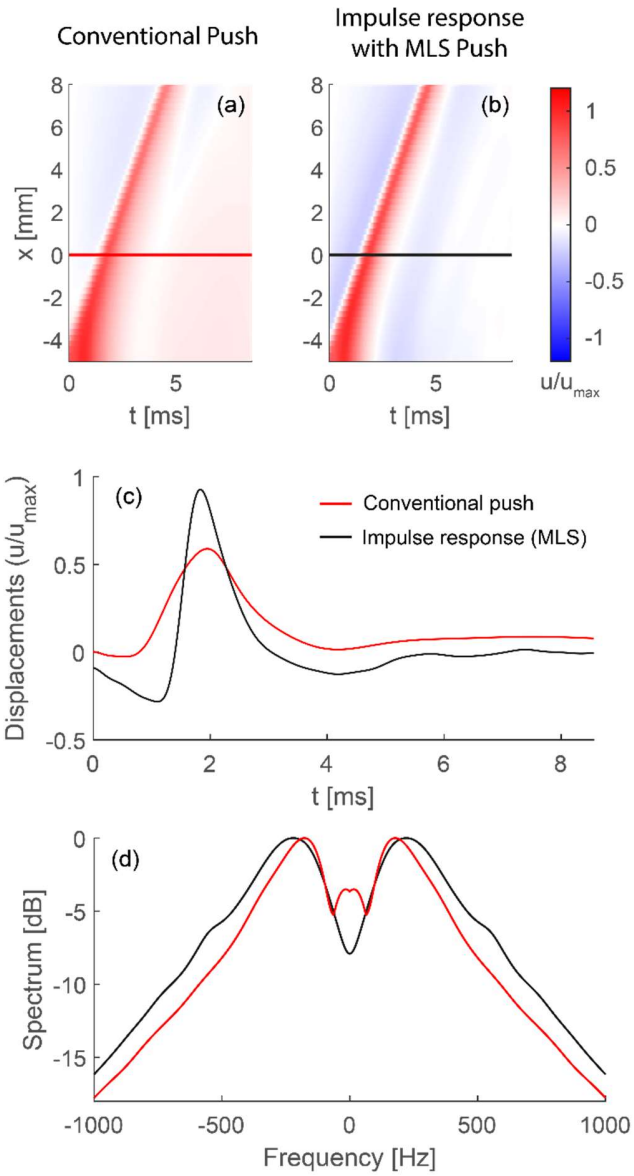


Figure 2. Comparison of the displacement map obtained using the conventional push method (a) and the proposed method (b). In figures (c) and (d), temporal and frequency analyses, respectively, are represented in a cross-section at x = 0 mm for the conventional case (red) and the impulse response obtained when exciting with MLS (black).

asymmetric [6]. This binary MLS sequence serves as the modulating signal $A(t)$ for the sinusoidal carrier signal with frequency ω_0, initial phase ϕ_0, and length N_{cycles},

$$x(t) = A(t)\sin(\omega_0 t + \phi) \quad (2)$$

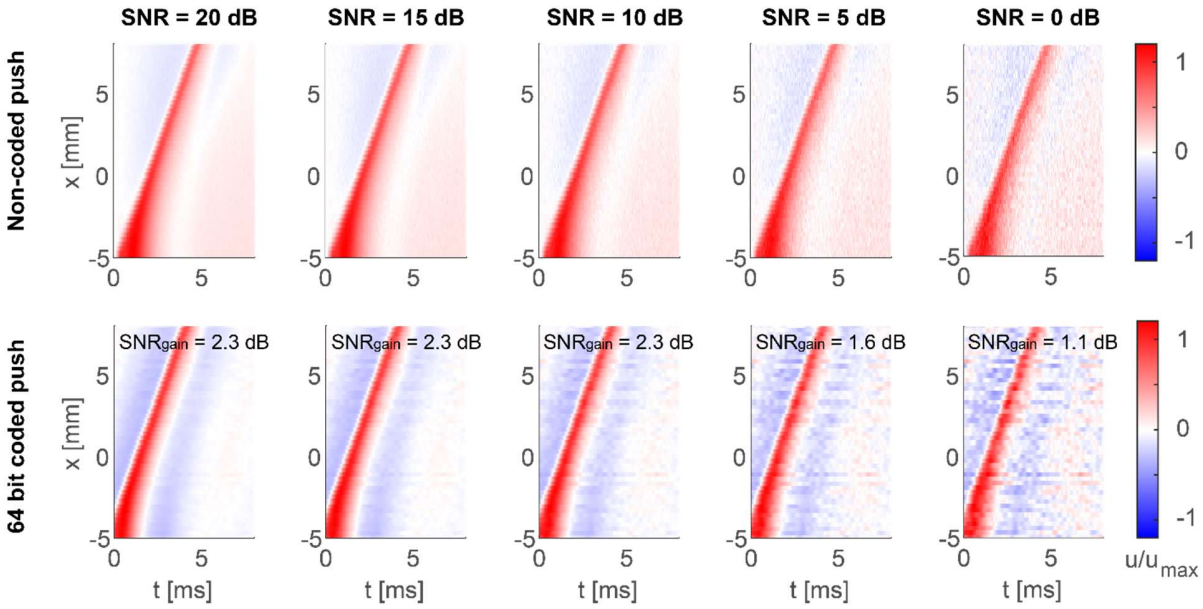


Figure 3. Comparison of the displacement maps obtained with the conventional push method (top row) with the impulse response obtained through coded push (bottom row) for different noise levels added. The lower row represents the signal to noise gain between both methods.

where t is the time vector. The result of the modulation, $x(t)$, is the high-frequency waveform that excites the medium, while $A(t)$ corresponds to the ARF that serves as the input to our LTI system. The modulation process is graphically represented in the upper block of Figure 1. The aim of exciting the medium with ARF is to generate stresses that can be translated into displacement terms, which form the output of our system, $y(t)$, as shown in Figure 1 below.

Once we have determined the input and output of our linear system, we can obtain the impulse response, $h(t)$, by deconvolution of the obtained displacements $y(t)$ with the amplitude-modulated ARF signal $A(t)$. Deconvolution can be performed in either the time or frequency domain. The classical approach involves frequency domain deconvolution as

$$h(t) = \mathcal{F}^{-1}\left[\frac{\mathcal{F}[y(t)]}{\mathcal{F}[A(t)]}\right] \tag{3}$$

where $\mathcal{F}$ and $\mathcal{F}^{-1}$ are the direct and inverse Fourier transforms, respectively. Using MLS signals for this type of inverse filtering approach is relevant since they are invertible, meaning there are no zeros in the Fourier domain. The result of the deconvolution supplies the impulse response of the system, as shown in the intermediate block of Figure 1.

To confirm the method, pseudospectral elastic simulations in the time domain were performed. The simulation involves figuring out the acoustic field of the simulated transducer. In this case, the acoustic field of a pulse focused at 20 mm was simulated using a 64-element phased-array transducer at a frequency of 2.72 MHz. This acoustic field serves as the input parameter for elastic simulations conducted using the k-Wave toolbox. A homogeneous elastic medium was simulated with the following parameters: propagation velocity of 1540 m/s, shear velocity of 2.45 m/s, density of 1000 kg/m³, and longitudinal absorption of 0.5 dB/MHz/cm.

Finally, a study was conducted to evaluate the improvement in signal-to-noise ratio (SNR) as a function of the MLS sequence degree. For this purpose, MLS-based ARF signals of three different degrees (N = 5, N = 6, and N = 7) were simulated. To assess SNR improvement when obtaining the impulse response, different levels of white Gaussian noise was added to the displacement signals obtained after exciting the medium with these signals. SNR was measured according to Equation (4), where P_S is the power of the signal of interest, and P_N is the power of the noise.

$$SNR = 10\log_{10}\left(P_s / P_N\right) \tag{4}$$

To compare the SNR enhancement the SNRgain was calculated as the ratio difference between the coded and non-coded excitation,

$$SNR_{gain} = SNR_{coded} - SNR_{non-coded} \tag{5}$$

3. RESULTS

To confirm the improvement in signal-to-noise ratio and bandwidth of the method, a comparison was made with the conventional method, which employs a single focused ARF pulse of shorter duration, typically between 500 and 1000 cycles. In contrast, the proposed method uses signals in the range of 20 to 100-103 cycles.

In Figure 2(a) and (b), displacement maps in the lateral direction over time are plotted. The maps show straight lines characterized by slopes, which can be described as the velocity of the medium in that specific region. To quantify the results more effectively, Figure 2(c) displays a time slice of the displacement at position $x = 0$ for both methods. It proves that the proposed method yields a more impulsive response compared to the conventional method, resulting in a broader bandwidth of the displacement response, as depicted in the frequency domain analysis in Figure 2(d).

Finally, to verify the improvement in the SNR ratio, Figure 3 presents the results of impulse response using a coded push excitation of 64 bits (N = 6). Different levels of gaussian noise from 0 to 20 dB, where 0 dB is the noisiest displacements. Although the displacement maps may look noisier in some of the coded cases, if we analyze the SNR individually for each map, we can see that the SNR gain is always positive, that means the SNR is higher for the coded sequences.

4. CONCLUSIONS

In this study, we introduced a coded excitation framework using pseudo-random signals to enhance the signal-to-noise ratio (SNR) in shear wave displacements within soft tissues. Through simulation studies, we demonstrate significant improvements in SNR by using pseudo-random sequence coded signals to amplitude modulate the radiation acoustic power. As future work, we propose to analyze the SNR improvement as a function of different levels of sequence length, in addition to experimental validations. These findings hold promise for advancing the field of elastographic ultrasound imaging, potentially improving its utility in clinical applications.

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