Shear-Wave Pulse-Compression Elastography using a Modulated Acoustic Radiation Force Excitation

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***Abstract*—Ultrasound shear wave elastography is a technique that induces shear waves in soft tissues through dynamic stress, thereby enabling the assessment of their elasticity by measuring wave velocity. However, limitations in ultrasound imaging, including shadowing, endogenous motion, reverberation, and depth-dependent attenuation, often result in low signal-to-noise ratio (SNR) signals, which present significant challenges for capturing shear waves. To address this issue, we propose a novel shear wave generation method based on acoustic radiation force (ARF) pulses modulated with binary maximum-length sequences (MLS). The method employs a binary-modulated ARF to induce tissue motion, which is then deconvolved with the pulse-coded excitation. The MLS deconvolution results in a broadband impulse response, thereby enabling the recovery of the compressed shear-wave pulse shape over the excitation frequency band and, moreover, enhancing the displacement amplitude and SNR. The initial experimental outcomes indicate that the use of extended coded-excitation ARF pulses results in an SNR gain exceeding 10 dB, attributable to pulse compression. By enhancing the quality of displacement data and reducing noise, the method fortifies the reliability of algorithms utilized to estimate shear wave speed, minimizing the potential for biased outcomes.**

***Index Terms*—Shear wave elastography, Pulse Compression, MLS**

I. Introduction

Elastography has emerged as a significant advancement in medical imaging, providing valuable insights into the mechanical properties of soft tissues. Unlike traditional imaging methods, elastography quantifies tissue elasticity, which aids clinicians in diagnosing and characterizing conditions such as fibrosis and prostate cancer through a combination of anatomical and quantitative imaging techniques [1], [2].

The assessment of tissue elasticity involves three key stages. First, shear waves are generated within the tissue, traveling at relatively low speeds (1.5 to 10 m/s) compared to the speed of sound in soft tissues, which is about 1540 m/s. These waves can be produced using two primary methods: passive excitation, involving external mechanical forces, and dynamic excitation techniques, particularly acoustic radiation force (ARF). The second stage focuses on capturing the displacements of these shear waves using various imaging modalities, such as magnetic resonance imaging, ultrasound, and optical techniques. In the final stage, shear wave velocity is calculated from the collected tissue motion data. This information is essential for determining the mechanical properties of the tissue, which, under ideal elastic conditions, can be related to Young's modulus, expressed as $E = 3c_s^2\rho_0$, where c_s is the shear wave velocity and ρ_0 is the density of the medium being analyzed.

Pulse compression is a method that employs coded excitations for the analysis of the impulse response of linear time-invariant (LTI) systems. This technique is commonly employed in a variety of applications, including communications such as radar and sonar technologies [3], [4], as well as medical ultrasound imaging [5], [6]. Furthermore, it has been employed in ultrasound elastography, albeit with passive excitation techniques as observed in transient elastography [7]. The principal objective of utilising coded excitation is to augment the signal-to-noise ratio (SNR) of the measured medium. The quality of elastographic imaging is contingent upon the precision of shear wave displacement measurements, which can be influenced by factors such as depth-dependent attenuation, reverberation or shadowing.

In this study, we introduce a novel method for dynamic shear wave generation using long ARF pulses amplitude modulated with maximal length sequences (MLS). This approach allows for the delivery of greater energy into the tissue without exceeding permissible intensity limits. An MLS is a pseudo-random binary sequence characterized by a period of $2^N - 1$, generated from a linear recursive algorithm of degree N [8]. These sequences are well-known for their high SNR and resilience against impulsive noise, making them particularly effective in acoustic applications [9]. The principal objective of our methodology is to enhance the SNR by calculating the impulse response of the medium through the application of pulse compression techniques. The subsequent sections will delineate the theoretical tenets underpinning this approach and present the findings from the inaugural experimental validation.

II. Methods

The operational framework of the proposed method is illustrated in Fig. 1. This technique employs broadband excitation signals, specifically pseudorandom sequences, to derive the

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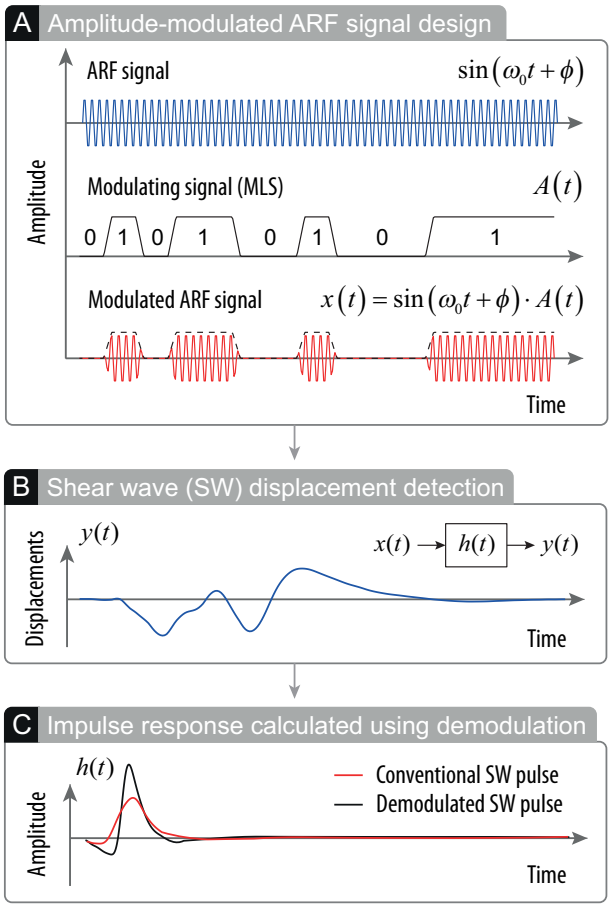


Fig. 1. Graphic diagram of the linear time-invariant system. The upper block (A) refers to the system input x(t), which results from modulating an ARF signal with an MLS signal. The middle block (B) is the system output in terms of displacement $y(t)$ generated by exciting the medium with $x(t)$. Ultimately, the lower block (C) represents the result of the deconvolution process, which yields the impulse response of the medium, $h(t)$.

impulse response of the medium, under the assumption that it behaves as a Linear Time-Invariant (LTI) system.

The initial step involves generating a pseudorandom MLS of degree N [10]. The SNR improvement depends on the code length and is proportional to $10\log_{10}(N)$. Therefore, it is advantageous to create long binary codes that are both invertible and asymmetric [9]. This binary MLS sequence functions as the modulating signal $A(t)$ for a sinusoidal carrier signal defined by frequency ω_0, initial phase ϕ, and duration N_{cycles}, $x(t) = A(t)\sin(\omega_0 t + \phi)$, where t represents the time vector. The output of this modulation process, $x(t)$, is a high-frequency waveform that excites the medium, while $A(t)$ denotes the coded amplitude modulation, serving as the input to our LTI system. The objective of applying ARF to the medium is to generate stresses that can be translated into displacement terms, resulting in the system's output $y(t)$, as illustrated in Fig. 1(B). Upon determining the input and output of our linear system, we can obtain the impulse response $h(t)$ through the deconvolution of the displacements $y(t)$ with the amplitude-modulated ARF signal $A(t)$. Deconvolution can be

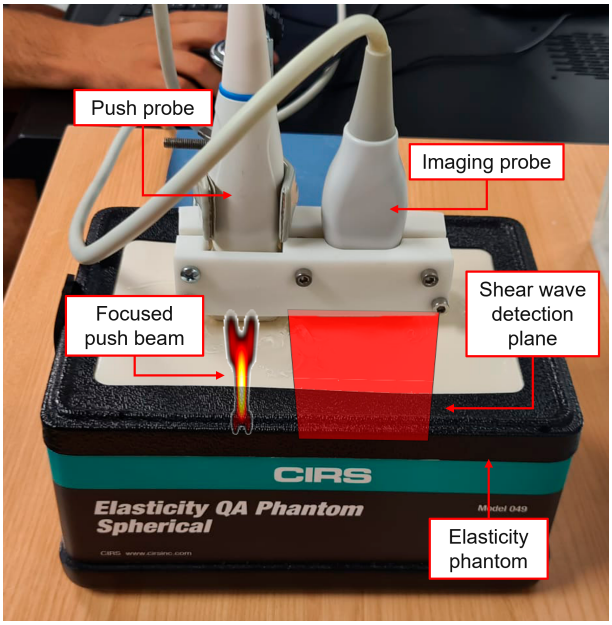


Fig. 2. The experimental setup comprises two probes: one for pushing the tissue and another for detecting the shear wave motion resulting from the tissue deformation. The experiments were conducted in a CIRS tissue-mimicking phantom.

executed in either the time or frequency domain. Utilizing MLS signals for this inverse filtering approach is significant due to their invertibility, which implies the absence of zeros in the Fourier domain. The result of this deconvolution yields the impulse response of the system, as shown in Fig. 1(C).

To validate the proposed method, experiments were conducted using a CIRS 049 elasticity phantom (Norfolk, VA, USA). The Vantage Research Ultrasound System 256 (Verasonics Inc) was employed, incorporating two ultrasound probes: one for compressing the soft tissue and another for monitoring displacements. Fig. 2 illustrates the experimental set up. The pushing probe consists of a 2.7 MHz 64-element transducer. For the modulated push signal, a binary MLS signal of $N = 6$ was utilized, resulting in a total of 63 bits. Each bit corresponds to a 100 μs push beam focused at a depth of 15 mm using 32 elements. In this setup, half of the bits are assigned a logical one, while the remaining bits are assigned a logical zero. Consequently, the total duration during which the bit is set to one is equivalent to 3.2 ms. An external power supply was used to drive the push transmit with an input voltage of 20 V. To track displacements, a 7.5 MHz 128-element linear array was utilized with a Pulse Repetition Frequency (PRF) of 10 kHz.

Finally, the improvement of the proposed method was assessed by measuring the signal-to-noise ratio according to SNR $= 10\log_{10}(P_S/P_N)$ where P_S represents the power of the signal of interest, and P_N denotes the noise power along a lateral cut at a fixed depth. To quantify the enhancement in SNR, the SNR gain was calculated as the ratio difference between the demodulated method and the conventional one-push method.

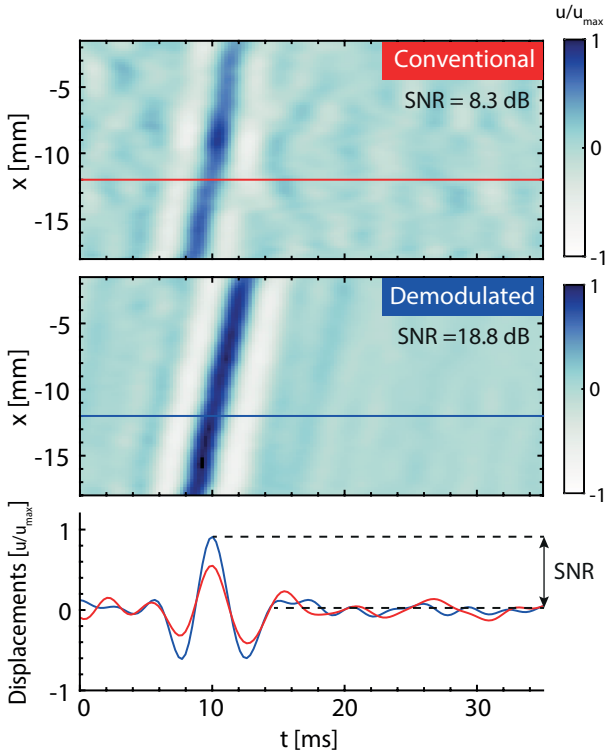


Fig. 3. Comparison of the normalized displacement map obtained using the conventional short push and the demodulated pulse compression method. Finally, a temporal analysis is represented in a cross-section at x = -12 mm for the conventional case (red) and the impulse response obtained when exciting with the coded excitation ARF (blue).

III. Results

To confirm the improvement in signal-to-noise ratio of the method, a comparison of the conventional method, which employs a single focused ARF pulse of relatively short duration, typically on the order of microseconds, with the proposed method, which employs pulses of longer duration, on the order of milliseconds, was undertaken.

Fig. 3 shows the shear motion maps measured along the lateral distance at a depth corresponding to the push focus comparing the proposed method with conventional push. The 2D 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, Fig. 3 displays a time slice of the displacement at position $x = -12$ mm for both methods. The results of the SNR analysis for this straightforward case demonstrate that the proposed demodulated approach yields an SNR of 18.8 dB, whereas the conventional method of a simple push results in an SNR of 8.3 dB. This leads to a SNR gain of over 10 dB.

The rationale behind this enhancement is that by transmitting longer pulses, a greater amount of energy is transmitted over time, thereby improving the SNR. Furthermore, the time-bandwidth product is responsible for determining the SNR improvement, as the use of longer pulses results in a higher SNR gain without the necessity of increasing peak power. This is of paramount importance for the detection of weak signals in noisy environments, ultimately leading to more accurate and reliable shear wave motion measurements.

IV. Conclusions

In this study, we proposed a coded excitation framework utilizing pseudo-random signals to enhance the SNR in shear wave displacement measurements within soft tissues. A straightforward experimental investigation demonstrated that the use of pseudo-random sequence-coded signals to modulate the amplitude of the acoustic radiation force significantly enhances the SNR. This improvement in displacement data quality and noise reduction serves to reinforce the reliability of the algorithms employed to estimate shear wave speed, thereby reducing the probability of biased outcomes.

In the future, several avenues of research may be pursued. One area of interest is the implementation of the method with a single probe, both for generating and detecting displacements, with the aim of improving practicality and ease of use. This approach could facilitate a broader range of analyses, including further optimization of SNR at varying sequence lengths, refinement of group velocity maps of shear waves, and expansion of the frequency bandwidth of deformations to better measure dispersion parameters.

References

[1] Castera, L., Forns, X. & Alberti, A. Non-invasive evaluation of liver fibrosis using transient elastography. *Journal Of Hepatology*. **48**, 835-847 (2008,5,1)

[2] Pallwein, L., Mitterberger, M., Struve, P., Pinggera, G., Horninger, W., Bartsch, G., Aigner, F., Lorenz, A., Pedross, F. & Frauscher, F. Real-time elastography for detecting prostate cancer: preliminary experience. *BJU International*. **100**, 42-46 (2007)

[3] Cook, C. Pulse Compression-Key to More Efficient Radar Transmission. *Proceedings Of The IRE*. **48**, 310-316 (1960,3)

[4] Fowle, E., Carey, D., Vander Schuur, R. & Yost, R. A pulse compression system employing a linear FM Gaussian signal. *Proceedings Of The IEEE*. **51**, 304-312 (1963)

[5] Chiao, R. & Hao, X. Coded excitation for diagnostic ultrasound: a system developer's perspective. *IEEE Transactions On Ultrasonics, Ferroelectrics, And Frequency Control*. **52**, 160-170 (2005)

[6] He, X.-N. et al. Improved shear wave motion detection using coded excitation for transient elastography. Sci. Rep. 7, 44483; doi: 10.1038/srep44483 (2017).

[7] Nguyen, T., Song, S., Arnal, B., Wong, E., Huang, Z., Wang, R. & O'Donnell, M. Shear wave pulse compression for dynamic elastography using phase-sensitive optical coherence tomography. *Journal Of Biomedical Optics*. **19**, 016013 (2014)

[8] Schroeder, M. Integrated-impulse method measuring sound decay without using impulses. *The Journal Of The Acoustical Society Of America*. **66**, 497-500 (1979,8,1)

[9] Bleakley, C. & Scaife, R. New formulas for predicting the accuracy of acoustical measurements made in noisy environments using the averaged m-sequence correlation technique. *The Journal Of The Acoustical Society Of America*. **97**, 1329-1332 (1995,2,1)

[10] Buračas, G. & Boynton, G. Efficient Design of Event-Related fMRI Experiments Using M-Sequences. *NeuroImage*. **16**, 801-813 (2002,7,1)