Ultrafast Ultrasound Imaging Using Simultaneous Emission of Plane Waves with Random Phases

Victor H. R. Machado, Tatiana de A. Prado, Thiago A. R. Passarin, Glauber Brante, Joaquim M. Maia, Daniel R. Pipa

***Abstract*— Plane wave imaging (PWI) is an ultrasound imaging technique that enables rapid non-destructive testing (NDT). PWI utilizes wavefields with higher amplitudes compared to the conventional synthetic aperture approach. However, achieving optimal imaging through the coherent plane wave compounding (CPWC) reconstruction requires numerous plane wave emissions with different angles. This work employs the simultaneous emission of coded plane waves. For this, each plane wave is generated with random-phase signals and separated using a matched filter in post-processing. Our results indicate that it is possible to apply the proposed concept, but improvements are needed to achieve performance equivalent to non-simultaneous uncoded waves.**

***Keywords*— Ultrafast ultrasound, coded signals, plane wave imaging.**

I. Introduction

The use of ultrafast ultrasound is a field of interest both in the biomedical field [1] and for the use in NDT [2]. Among the usual ultrasound imaging methods, using PWI combined with CPWC yields good images and reduces signal acquisition time. In PWI, the elements of the transducer are combined to trigger a single wave, resulting in a wave with higher energy than those emitted by the individual elements [3]. However, to ensure quality, the CPWC depends on multiple and successive emissions of plane waves with different angles [4].

Simultaneous emission of multiple plane waves can be performed by means of coded excitation. Arbitrary waveform coded excitation is a technique that transmits a long sequence of coded pulses and, upon reception, compresses the echo into a pulse of short duration and high amplitude to restore axial resolution [5]. The use of coded signals in ultrasound improves signal penetration, signal-to-noise ratio (SNR), and acquisition speed [6]. Coding is performed using orthogonal sequences, which can be applied in phase, frequency, or amplitude modulation. Then, coded signals can be uniquely identified by the orthogonal sequence used in its modulation. Thus, overlapping signals can be separated due to their orthogonality, using, *e.g.*, correlation-based matched filtering [7].

The SNR of the signal after the matched filter is equal to the time-bandwidth product [8]. Therefore, the signals to be coded must occupy all the transducer available bandwidth and time, given its structural limitations. A comprehensive analysis of signal encoding types [9] shows that coded random-phase signals exhibit superior correlation properties, with smaller sidelobes when utilizing a predefined spectrum in signal design, which motivates us to use random-phase encoding.

This paper evaluates the feasibility of employing simultaneous random-phase signals in PWI acquisition, using a matched filtering separation technique in post-processing, and image reconstruction using CPWC for NDT applications. We aim to increase the acquisition speed by simultaneously employing three coded plane waves at different angles, while keeping similar SNR compared to the acquisition using a single and uncoded wave. Note that a single uncoded wave employs shorter pulses at the transducer, yielding good image resolution, while coded transmissions require longer sequences.

II. Materials and Methods

A sinusoidal ultrasound random-phase signal is defined as:

$$s(t) = \cos\left[2\pi f_{\mathrm{c}} t + 2\pi\alpha X(t)\right], \tag{1}$$

where f_{c} is the central frequency of the transducer, $X(t)$ is a pseudo-random sequence used for encoding, drawn from the interval $[0, 1)$, and α is a parameter to adjust the randomness level of the signal phase.

To be used as the matched filter, the signal $s(t)$ undergoes a forward-backward filtering process to zero out the filter phase response [10]. This is achieved by employing a first-order Butterworth bandpass filter, whose central frequency equals f_{c} and the cutoff frequencies follow the transducer bandwidth. The output of this process yields the filtered signal $\hat{s}(t)$.

Next, we define the excitation matrix $\mathbf{A}$, containing the signals that each transducer element will emit over time. It is computed using the signal $\hat{s}(t)$, sampled at the transducer sampling frequency f_{s}, generating a plane wave with angle θ to be emitted at the transducer output, as follows:

$$\mathbf{A}_{ij} = \hat{\mathbf{s}}_l \tag{2}$$

$$\text{with: } l = \lceil i - j\,\frac{p\,\sin[\theta]\,f_{\mathrm{s}}}{c} \rfloor, \tag{3}$$

where l is the delay due to the angle θ, p is the pitch, $\hat{\mathbf{s}}$ is the signal $\hat{s}(t)$ sampled using f_{s}, c is the speed of sound in the inspected material, $j \in [1, \ldots, N_{\mathrm{e}}]$, $i \in [1, \ldots, N_t]$, N_{e} is the number of transducer elements, N_t is the number of samples in time and $\lceil \rfloor$ denote the nearest integer function.

Then, the simultaneous emission of plane waves usually combines sequences with different angles, so that the emission matrices for each angle θ are summed into a single matrix, which is then used by the ultrasound system to excite the transducer. On the other end, in order to separate the emitted plane waves, the signal received is filtered by the matched filter as follows:

$$\hat{\mathbf{Y}}_{ij}^{k} = \mathbf{Y}_{ij} \star \hat{\mathbf{s}}_{i}^{k} \tag{4}$$

where $\mathbf{Y}_{ij}$ is the signal received by the j-th transducer element in time sample i, $k \in [1, \dots, N_\theta]$, N_θ is the number of employed angles, $\hat{\mathbf{s}}_i^k$ is the sampled signal associated with the angle θ_k, while $\star$ represents the discrete-time correlation.

The discrete Hilbert transform [10] of $\hat{\mathbf{Y}}$ on the time axis is used as input to the CPWC algorithm [2], whose absolute output value yields an image representing the acoustic reflectivity of the region of interest.

III. Results

Our experiment used the Verasonics Vantage 128 ultrasound acquisition system coupled with an L11-4v transducer. The transducer has a central frequency $f_\mathrm{c} = 7.25$ MHz, a bandwidth of 6.78 MHz, 128 elements, and a pitch of $p = 0.3$ mm. The sampling frequency at reception is $f_\mathrm{s} = 27.78$ MHz. The system uses a ternary pulse width modulation (PWM) excitation to send arbitrary signals. Thus, the excitation matrix is converted into ternary signals by the Vantage system.

The setup consists of a 0.12 mm diameter metallic wire immersed in water at a depth of 60 mm below the center of the transducer. Three experiments were performed. First, a single uncoded plane wave with 0° was fired. Second, three uncoded plane waves are fired at different times (*i.e.*, not simultaneously) with angles $-3°$, $0°$, and $3°$. Such a scenario yields the highest resolution at the cost of increased acquisition time. Third, three random-phase codes are generated using $\alpha = 1$. The plane waves are simultaneously fired with angles $-3°$, $0°$, and $3°$, and separated upon reception via matched filters for each respective code. Here we increase the acquisition speed threefold at the cost of some interference among the simultaneous waves.

A Python implementation of the CPWC algorithm was used for image reconstruction, with results shown in Fig. 1. In the non-simultaneous excitation experiments, Figs. 1(a) and 1(c), the artifacts in the horizontal axis around the reflector are expected due to the small number of angles used in the acquisition. In the simultaneous excitation, Fig. 1(b), the main artifacts appear with vertical orientation due to the interference between signals in the matched filtering and the non-ideal auto-correlation that deviates from a unit impulse.

Table I shows the SNR of the experiments, which was calculated around the reflector in a region between -15 mm and 15 mm on the horizontal axis and between 50 mm and 70 mm on the vertical axis. The signal level considered is above -6 dB. As we observe, the SNR when using 3 simultaneous coded plane waves is 5.2 dB lower than that with a single uncoded wave, while using three non-simultaneous uncoded plane waves yields the highest SNR.

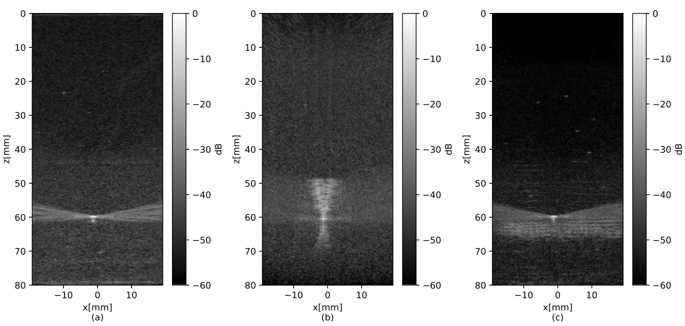

Fig. 1. CPWC algorithm image reconstruction. (a) 1 angle, uncoded. (b) 3 angles, coded, simultaneous. (c) 3 angles, uncoded, not simultaneous

TABLE I

SNR of the image for each experiment.

	SNR (dB)
1 angle, uncoded	33.7
3 angles, coded, simultaneous	32.3
3 angles, uncoded, not simultaneous	37.5

IV. Conclusions

Despite increasing the acquisition speed, the use of simultaneous coded plane waves for ultrasound imaging with random-phase signals and correlation filters still needs to be improved in terms of SNR, compared to using non-simultaneous uncoded plane waves. Possible approaches would be to consider the attenuation effects of the inspected material, as well as the conversion of the ultrasound acquisition system to the ternary PWM signal in order to build a correlation filter that more closely resembles the signal received by the transducer. Other types of filters can also be studied, such as Wiener and inverse filters [8], as well as other ways to reconstruct the region of interest, *e.g.*, using inverse problems [4].

Aknowledgements

This study was financed by the Human Resource Program of The Brazilian National Agency for Petroleum, Natural Gas, and Biofuels – PRH-ANP – FINEP Management, contractual instrument n° 0.1.19.0240.00, Ref 0431/19 - PRH21-UTFPR, PETROBRAS/CENPES by project AUSPEX, CNPq through grant 316234/2021-4, and CAPES - Finance Code 001.

References

[1] M. Tanter and M. Fink, "Ultrafast imaging in biomedical ultrasound," *IEEE Transactions On Ultrasonics, Ferroelectrics, And Frequency Control*, vol. 61, pp. 102–119, 2014.

[2] L. Le Jeune, S. Robert, E. L. Villaverde, and C. Prada, "Plane wave imaging for ultrasonic non-destructive testing: Generalization to multimodal imaging," *Ultrasonics*, vol. 64, pp. 128–138, 2016.

[3] G. Montaldo, M. Tanter, J. Bercoff, N. Benech, and M. Fink, "Coherent plane-wave compounding for very high frame rate ultrasonography and transient elastography," *IEEE Transactions On Ultrasonics, Ferroelectrics, And Frequency Control*, vol. 56, pp. 489–506, 2009.

[4] B. Denis, L. Hervé, and N. Barbara, "Simultaneous coded plane wave imaging in ultrasound: Problem formulation and constraints," *IEEE International Conference On Acoustics, Speech And Signal Processing (ICASSP)*, pp. 6254–6258, 2017.

[5] T. Jibiki, "Coded excitation medical ultrasound imaging," *Japanese Journal Of Medical Physics: An Official Journal Of Japan Society Of Medical Physics*, vol. 21, pp. 136–141, 2001.

[6] T. Misaridis, "Ultrasound imaging using coded signals," *Electronics & Signal Processing*, 2001.

[7] F. Gran and J. Jensen, "Spatial encoding using a code division technique for fast ultrasound imaging," *IEEE Transactions On Ultrasonics, Ferroelectrics, And Frequency Control*, vol. 55, pp. 12–23, 2008.

[8] T. Misaridis and J. Jensen, "Use of modulated excitation signals in medical ultrasound. part I: basic concepts and expected benefits," *IEEE Transactions On Ultrasonics, Ferroelectrics, And Frequency Control*, vol. 52, pp. 177–191, 2005.

[9] T. Dean, "The use of pseudorandom sweeps for vibroseis surveys," *Geophysical Prospecting*, vol. 62, no. 1, pp. 50–74, 2014.

[10] J. O. Smith, *Introduction to Digital Filters with Audio Applications*. W3K Publishing, 2007. [Online]. Available: http://www.w3k.org/books/