

Modeling and Removal of Electronic Crosstalk Effects in Ultrasound Signals via Deconvolution

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1 Abstract

The performance of an ultrasound array transducer is typically impaired by element-to-element interference, also known as crosstalk. The various approaches for reducing crosstalk generally involve modifying the transducer design or controlling the excitation waveforms. In this paper, we propose a method for modeling and removing electronic reception crosstalk in post-processing, which can serve as an alternative, or even a complement, to existing approaches. The modeling consists of estimating $N \cdot (N - 1)$ Finite Impulse Responses (FIRs) that represent the effect that each $(N - 1)$ -th channel of the Phased Array (PA) has on the other channels. To obtain this modeling, we have performed controlled acquisitions that capture supposedly ideal signals (free from crosstalk) on one channel at a time, physically blocking the remaining channels. As a consequence, blocked channels will only capture electronic crosstalk. After the modeling stage, crosstalk removal from arbitrary datasets acquired with the modeled PA is performed via a Tikhonov-regularized inverse problem using the estimated FIRs. Experimental results show that the proposed method is able to improve the Signal-to-Interference-plus-Noise Ratio (SINR) by up to 13.4 dB.

Keywords: Ultrasound inspections; System identification; Finite Impulse Response; Electronic crosstalk; Signal processing.

2 Introduction

Crosstalk in an ultrasound system can originate from either electrical or mechanical sources. Capacitive coupling caused by long parallel cables, high voltage, miniaturized circuits, and high-frequency signals are potential source of electrical crosstalk [1]. Phased Array (PA) transducers, due to their construction characteristics with many small piezoelectrical elements, are susceptible to electrical interference between elements. In addition, in subsea inspections, the use of long cables and high-pressure connectors worsens this effect.

In particular, crosstalk in signal reception can affect the accuracy and sharpness of the ultrasound image, potentially compromising its quality. In the literature, efforts to reduce crosstalk fall into two main approaches: passive crosstalk reduction methods that optimize structural design and the mechanical and electrical characteristics of the ultrasound system; implementing active cancellation techniques that utilize different excitation waveforms, system modeling, and noise suppression [1].

In scenarios where commercial transducers and ultrasound systems do not support arbitrary signal excitation, active methods for crosstalk minimization become crucial. A traditional application of adaptive noise cancellation to minimize crosstalk is presented in [2]. Although the method achieved the expected results in crosstalk removal, the results depend on the accuracy of the simulated reference crosstalk. Assuming that crosstalk echoes are highly correlated with the original signal and are time-smooth, a method based on Least Mean Square (LMS) adaptive filtering is presented by [3]. This method operates in the frequency

domain by separating the signal into subbands, estimating crosstalk using LMS adaptive filtering, and subtracting the signals sequentially. However, this method was validated only with simulated signals.

Alternatively, in this paper, we propose a post-processing method to remove crosstalk in real-world inspections. The proposed method is divided into two steps: pre-modeling of crosstalk effects from a specific transducer, assuming that they can be represented as Finite Impulse Responses (FIR); and the crosstalk removal via a Tikhonov-regularized inverse problem using the estimated FIR. The mathematical formulation of these steps is detailed in Section 3, and the results obtained by applying the method are presented in Section 4. Finally, the conclusions are summarized in Section 5.

3 Material and Methods

The following sections detail the two steps involved in the proposed method. Section 3.1 models crosstalk considering a controlled experiment, while Section 3.2 details the process of removing the crosstalk effect for arbitrary acquisition using the same PA.

3.1 Crosstalk Modeling

In ultrasound inspections using PAs, signals received in one channel can affect neighboring channels. To model this effect, we assume that given a controlled acquisition, it is possible to obtain the supposedly ideal signal (crosstalk-free) in a single channel and observe only the crosstalk effects in the other channels. Hence, assuming linearity, the problem of estimating the impulse response that represents the crosstalk effect can be expressed in terms of a linear operator [4]. Suppose that the j -th channel contains the ideal signal f_j , then F_j is the linear operator whose domain is the space of all possible impulse responses that describe the system, and whose co-domain is the space of A-scans. For $i \neq j$, if g_i is the observed signal in the i -th channel, it follows that

$$\hat{h}_{i,j} = \arg \min_{h_{i,j}} \|F_j(h_{i,j}) - g_i\|_2 + \epsilon \|h_{i,j}\|_1, \quad (1)$$

where $\hat{h}_{i,j}$ is the estimated impulse response representing the crosstalk effect that the signal received on channel j yields on channel i . Also, the inclusion of an ϵ -weighted ℓ_1 regularization guarantees that each $\hat{h}_{i,j}$ has adequate characteristics for convergence in the removal process. Moreover, assuming that $h_{i,j}$ is a FIR, we have that F_j is the convolution matrix with f_j as its kernel. The deconvolution presented in Eq. (1) can be achieved using Iteratively Reweighted Least Squares (IRLS) [5].

Solving Eq. (1) for each $i, j \in \mathbb{Z} \cap [1, N]$, we can build a new linear operator $\mathcal{H}_{\text{FIR}}$ expressed as

$$\mathcal{H}_{\text{FIR}}(f) = \sum_{i=1}^N \left(\sum_{j=1}^N f * h_{i,j} \right). \quad (2)$$

The linear operator maps the space of ideal B-scans onto the space of observed B-scans. The diagram shown in Fig. 1 summarizes the process of building $\mathcal{H}_{\text{FIR}}$.

3.2 Crosstalk Removal

After modeling the crosstalk effect in a controlled environment to obtain $\mathcal{H}_{\text{FIR}}$, we took advantage of the equivalence between a Tikhonov-regularized problem and the removal of crosstalk of arbitrary acquisitions using the same PA as the modeling process. The estimated B-scan after crosstalk removal, denoted by $\hat{f}$, can be written as

$$\hat{f} = \arg \min_f \|\mathcal{H}_{\text{FIR}}f - g\|_2^2 + \lambda \|f\|_2^2, \quad (3)$$

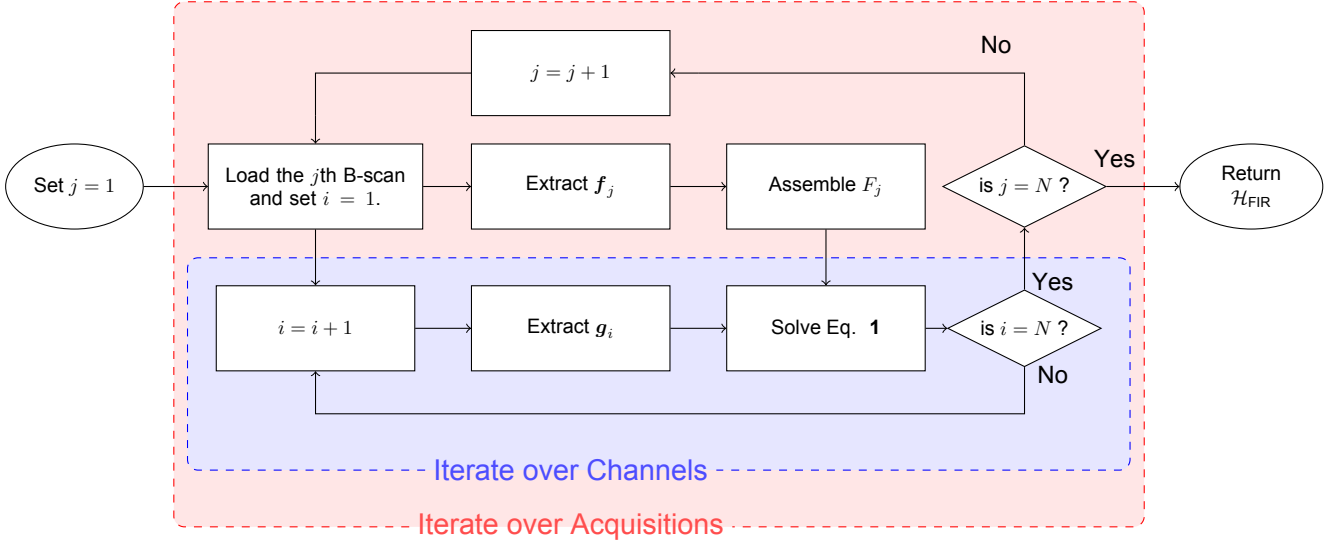


Fig. 1. Diagram of the crosstalk modeling process.

where the original B-scan (with crosstalk) is denoted by g and λ is the weight attributed to the ℓ_2 regularization, which is needed because Eq. (3) is ill-posed [5].

In order to solve Eq. (3) we have employed the Pylops library [6] using the Least Squares (LS) method, which handles the summation of convolutions inside nested for loops efficiently, as it is the case of the operator given by Eq. (2). In addition, since most operations involve large matrices, it is advantageous to implement the workflow in a matrix-free manner. The adopted halting condition is given by

$$\|\mathcal{H}_{\text{FIR}}^H \mathbf{r}\|_2 \leq \zeta \|\mathcal{H}_{\text{FIR}}\|_2 \|\mathbf{r}\|_2 \quad (4)$$

where $\mathcal{H}_{\text{FIR}}^H$ is the conjugate transpose of $\mathcal{H}_{\text{FIR}}$, ζ is the tolerance, and $\|\mathbf{r}\|_2 = \|\mathcal{H}_{\text{FIR}} \mathbf{f} - \mathbf{g}\|_2$ is the ℓ_2 -norm of the residual vector.

To evaluate the quality of the estimation, we made use of the Signal-to-Interference-plus-Noise Ratio (SINR), the Contrast-to-Noise Ratio (CNR) [7] and the Contrast Ratio (CR) [8] as performance metrics, which are respectively defined as

$$\text{SINR} = \frac{\|\mathcal{S}\|_2}{\|\mathcal{C}\|_2 + \|\mathcal{M}\|_2}, \quad (5a) \quad \text{CNR} = \frac{|\mu_{\mathcal{S}} - \mu_{\mathcal{C}}|}{\sigma_{\mathcal{C}}}, \quad (5b) \quad \text{CR} = \frac{\mu_{\mathcal{S}}}{\mu_{\mathcal{C}}}, \quad (5c)$$

where $\mathcal{S}$, $\mathcal{C}$ and $\mathcal{M}$ are the regions of the B-scans that contain only the intended signal, only crosstalk and only noise, respectively. Let us remark that we manually select $\mathcal{S}$, $\mathcal{C}$, and $\mathcal{M}$ based on masks from the obtained B-scans of the inspected object. Moreover, μ and σ^2 with respect to a given index $A \in \{\mathcal{S}, \mathcal{C}, \mathcal{M}\}$ are defined as $\mu_A = \mathbb{E}\{|A|^2\}$ and $\sigma_A = \mathbb{E}\{(|A|^2 - \mu_A)^2\}$.

4 Experiments and Results

The experiment to model and to remove electronic crosstalk was conducted using the Panther™ ultrasound system from Eddify® and the Acquire software. High-pressure PA transducers with a center frequency of 5 MHz, 64 channels, pitch 0.6 mm, and 10 m of cable were used.

To obtain signals for modeling crosstalk, we performed controlled acquisitions using two PA transducers: one as the emitter and the other as the receiver. Then, a triangular prism-shaped piece was placed between the transducers, as illustrated by Fig. 2a. The base of the prism was coupled to the transmitter, while the top of the prism was coupled to a single receiver channel in a pitch-catch setup. With this setup, a focused shot was emitted for each

receiver PA channel, and a high-energy signal was recorded. Thus, for each experiment, a single receiver channel receives a quasi-ideal signal, while its neighbor channels perceive mainly crosstalk. Fig. 2b shows the B-scan (in decibel) of one of these experiments where the prism-shaped piece is coupled to the 32nd channel of the receiver. Visibly, the 32nd channel exhibits a high-energy signal corresponding to the emitted pulse, while all other 63 channels observe electronic crosstalk with smaller energy.

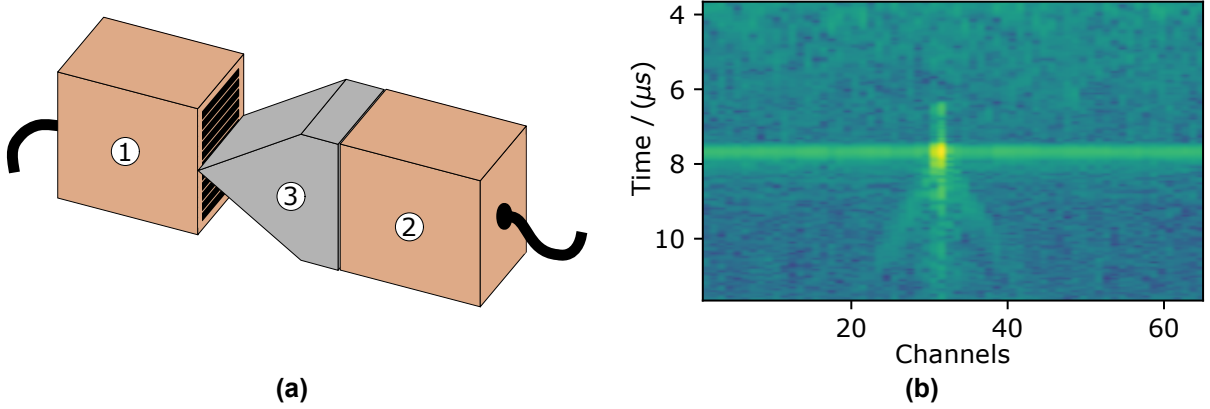


Fig. 2. Setup and signal in modeling step. (a) The transducer 1 acts as a receiver and the transducer 2 as a transmitter. Between them, there is a metallic specimen in the shape of a triangular prism, whose tip is in contact with a single element of transducer 1 and whose base is completely coupled to transducer 2. (b) Control acquisition for acquiring the quasi-ideal signal in channel $j = 32$ and crosstalk in the other channels.

Then, controlled acquisitions for every channel of the receiver PA follow the workflow illustrated in Fig. 1. We assume that each impulse response has a length of 50 samples and $\epsilon = 10^{-5}$ (chosen empirically). To ensure that each estimated FIR behaves as expected, we manually checked, for each controlled acquisition, how each $F_j(\hat{h}_{i,j})$ approximates g_i . Setting $i = 3$ and $j = 6$, Fig. 3 presents the normalized (with respect to g_3) raw signal and the spectrum amplitude of $F_6(\hat{h}_{3,6})$ and g_3 , highlighted in black and red, respectively. In Fig. 3a we can see that $F_j(\hat{h}_{i,j})$ closely approximates the signal assumed as crosstalk. The noise present in the observed signal is characteristic of these inspections. Observing Fig. 3b, it can be seen that $\hat{h}_{3,6}$ acts as a band-pass filter, attenuating the portion of the signal that lies outside the set of frequencies that the transducer operates, which is represented by the region highlighted in blue. With this setup, the modeling process in its entirety takes less than 3 minutes running on an Intel(R) Core(TM) i7-14700KF processor.

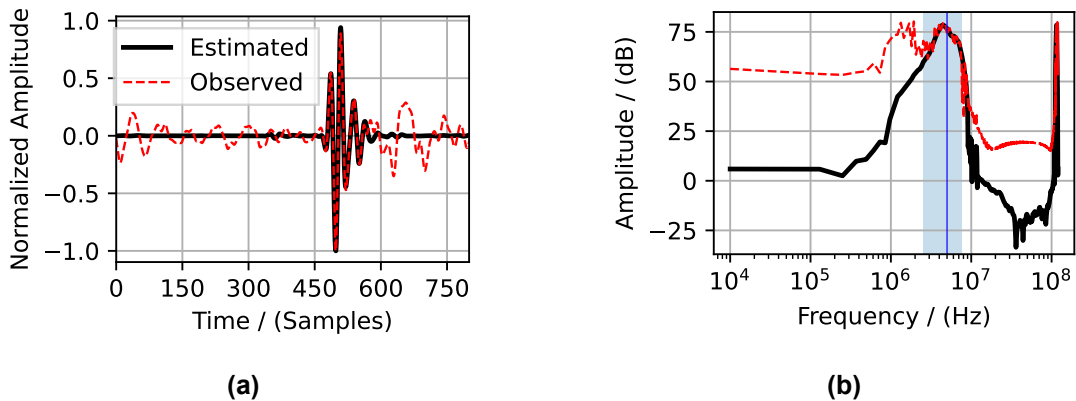


Fig. 3. Estimated crosstalk in the 3rd channel caused by a signal applied to the 6th channel. (a) Amplitude comparison between observed and estimated crosstalk; (b) Amplitude spectrum comparison between observed and estimated crosstalk. The vertical line represents the transducer's ideal central frequency, while the highlighted area represents the ideal bandwidth.

To demonstrate the crosstalk removal, we employed the same transducer used in the modeling process to inspect a flat, inclined surface coupled with tap water, as shown in Fig. 4a. Then, we shot a plane wave with a steering angle of 0° yielding a total of 64 A-scans, each containing 1875 samples. In this process, we empirically adopted $\lambda = 6 \cdot 10^{-5}$ and $\zeta = 10^{-8}$. Fig. 4b presents the B-scan of the raw data for the current setup. The diagonal area marked in red corresponds to $\mathcal{S}$, *i.e.*, the region where the echoes reflected from the surface of the inspected specimen are expected. The region marked in blue represents $\mathcal{C}$, where a high-intensity noise can be observed due to crosstalk generated by each channel when receiving echoes from the surface. In addition, the orange region ($\mathcal{M}$) represents only noise. Fig. 4c shows the B-scan after removing the crosstalk with the proposed method. As we observe, the entire region to the right of the surface is now very similar to structural noise, indicating that the crosstalk has been properly removed.

The image quality metrics are summarized in Table 1, and confirm the effectiveness of the proposed method. In this case, the removal of crosstalk improved the CR by 8.1 dB, the CNR by 11.9 dB, and the SINR by 13.4 dB. The metrics shows how much crosstalk removal can improve the visual sharpness of the reflector in the inspection area.

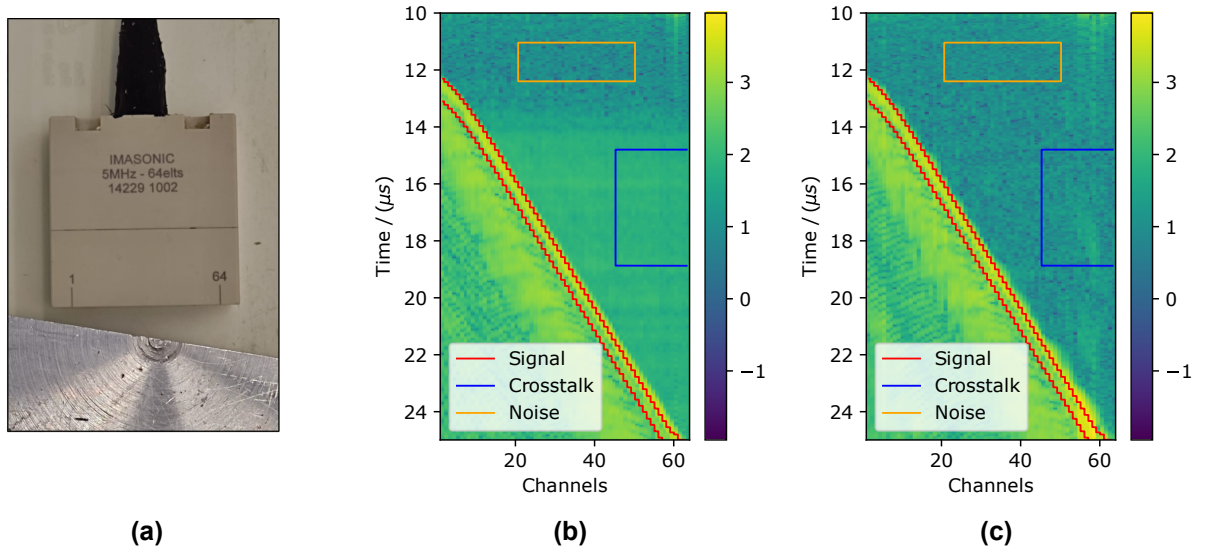


Fig. 4. A particular experimental setup with and without the proposed crosstalk removal. (a) Experimental setup where all components are underwater; (b) Original B-scan (log-scale) with crosstalk on the upper diagonal; (c) Estimated B-scan (log-scale) by proposed method with significantly less crosstalk.

Table 1: Metrics for evaluating the image quality.

	CR	CNR	SINR
Before post-processing	47.3 dB	27.8 dB	29.2 dB
After post-processing	55.4 dB	39.7 dB	42.6 dB

Finally, Fig. 5 shows the ℓ_2 -norm of the removal process ($\|r\|_2$) and the metrics at each iteration. At iteration 0, each metric is calculated from the original B-scan. Then, we observe that after the 50-th iteration, all metrics have a variance smaller than 2 dB. Nevertheless, $\|r\|_2$ only converges after the 150-th iteration. In our setup, the LS method continues the minimization until it is stopped at the 264-th iteration by the halting condition in Eq. (4).

5 Conclusion

Considering ultrasound systems where excitation cannot be controlled and commercial array transducers, we proposed a method for crosstalk removal in post-processing, which

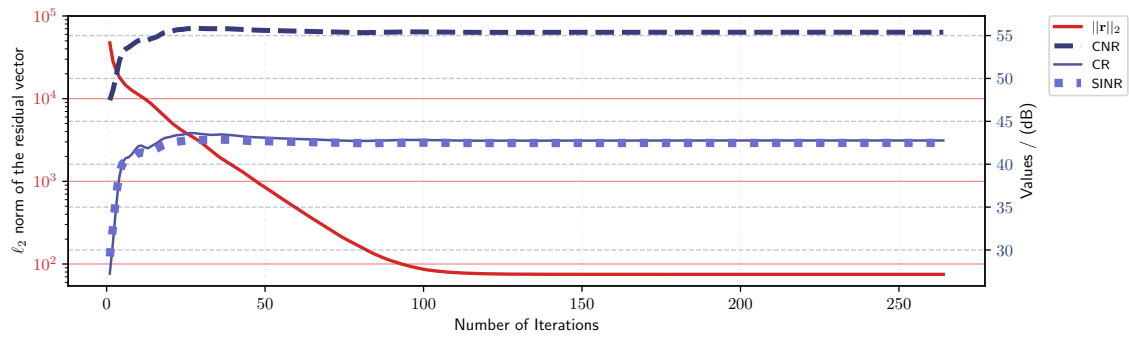


Fig. 5. Evolution of the metrics in log-scale, comparing the residue, CR, CNR, and SINR as a functions of the number of iterations.

achieved an improvement of more than 10 dB for CNR and SINR in the validation test. Since crosstalk is intrinsic to the ultrasound system, the modeling is performed only once for a transducer-ultrasound system set, and these results can be used to remove crosstalk from any acquisition performed with the same system. Future work includes modeling with other transducer configurations, new mathematical approaches, and validation testing on defective specimens in order to observe improvements in flaw detectability.

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