Adaptive Time Corrected Gain for Ultrasound Through Time-Varying Wiener Deconvolution

Daniel R. Pipa
Department of Electrical Engineering
Federal University of Technology
Curitiba, Paraná, Brazil
Email: danielpipa@utfpr.edu.br

Giovanni A. Guarneri
Department of Electrical Engineering
Federal University of Technology
Pato Branco, Paraná, Brazil
Email: giovanni@utfpr.edu.br

Hector L. de Moura
Department of Electrical Engineering
Federal University of Technology
Curitiba, Paraná, Brazil
Email: hector@alunos.utfpr.edu.br

***Abstract*—Ultrasound testing techniques, either non-destructive (NDT) or medical, suffer from spatial signal attenuation, where equivalent scatterers at different distances from the transducer will display different signal amplitudes. If not corrected, these differences may lead to erroneously interpretation.**

In NDT, Time Corrected Gain (TCG) compensates for spatial attenuation by increasing input gain according to the expected attenuation. Because TCG does not consider noise, signals coming from far scatterers are highly amplified, and so is noise. Wiener filter, on the other hand, deal with noise optimally, but does not compensate for spatial attenuation.

In this paper, we propose an Adaptive TCG that combines the amplitude correction of the TCG with the optimality of the Wiener filter. We present simulations to evaluate the robustness of the proposed technique, as well as real-word results showing the the proposed method is superior to both Wiener filter and classical TCG independently.

I. Introduction

Propagation of mechanical waves usually suffers attenuation from several sources, such as beam spreading (geometrical), material grain scattering and absorption. Time corrected gain (TCG) is an important pre-processing for non-destructive testing (NDT) ultrasound that aims to correct and eliminate the effect of attenuation by appropriate amplification of the acquired signal. As the attenuation increases with distance, TCG has also to be *space-variant* ou *time-variant* if we consider the acquisition process.

A similar approach is the use of DAC (distance amplitude correction) curves. DAC curves, which relate the attenuation with distance, are usually obtained from a sets of reference specimens for every different testing situation. Thus, an inspector, knowing the distance, can correct the expected signal amplitude that a defect with acceptable dimensions generates when reflecting the ultrasound [1].

On the other hand, TCG *corrects* the amplitude and the above analysis can be performed as if the defect was in contact with the transducer in terms of signal amplitude. In more sophisticated reconstruction algorithms, TCG enables the modelling of the ultrasound system as a LTI system [2]. Specifically, attenuation is omitted in most linear models used by these reconstruction algorithms. However, if these effects are not compensated by a TCG, the performance of the algorithms may degrade [3].

A. Related Word

Time-varying Wiener filters have been previously developed using diverse strategies and for different applications. In [4], the filter was based on the Short-Time Fourier Transform to denoise magnetocardiographic signals. In [5], adaptive Wiener filters based on the NLMS and RLS algorithms were employed to estimate a time-varying channel in wireless OFDM systems. In [6], the author presents a time-varying wiener deconvolution where the reference signal was assumed to be a wavelet

In terms of adaptive TCG, in [7] the authors propose the use of pattern recognition techniques to apply different correction gain depending on the detected feature. In [8], an adaptive TCG is proposed where the “adaptation” is a parametric determination of attenuation parameters.

Differently from the works found in the literature, we propose an adaptive TCG based on Wiener deconvolution. The methods combines the attenuation correction of TCG with the optimal trade-off of Wiener.

II. Observation Model

Suppose we are probing with ultrasound signals a medium containing M reflective interfaces (scatterers) within the cone beam of the transducer.

$$x(t) = \sum_{i=1}^{M} f(t - d_i) \tag{1}$$

where , $f(t)$ is the echo prototype, M is the number of echoes or scatterers, d_i is the delay caused by the scatterer distance and we assume that all scatterers reflective coefficients are 1.

A typical NDT ultrasound signal obtained in such a test can be modelled by

$$g(t) = a(t)x(t) + n(t), \tag{2}$$

where $a(t)$ is time-varying attenuation and $n(t)$ is an i.i.d. Gaussian noise signal with variance σ^2 that models all sources of additive noise.

The main sources of attenuation are scattering and absorption. The former is due to small crystalline grains into metal of the inspected object. The latter is due to conversion of mechanical energy into heat during wave motion [9]. In general, the attenuation can be modeled by [1]

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$$a(t) = \exp(-\beta(\Omega)t), \tag{3}$$

where $\beta(\Omega)$ is the attenuation coefficient. Although the attenuation coefficient is frequency-dependent, in many NDT applications it is considered constant in frequency, i.e. $\beta(\Omega) \approx \beta_m$, where β_m is referred to as *attenuation coefficient of the material* [9].

III. Wiener Filter and Classical TCG

The Wiener filter is a linear time-invariant system that achieves the optimum trade-off solution, in a least-squares sense, to recover a signal embedded in noise. If a signal is observed through a linear operator with AWGN, i.e.

$$g(t) = (h \star x)(t) + n(t), \tag{4}$$

which can be expressed in the frequency domain as

$$G(\Omega) = H(\Omega)X(\Omega) + N(\Omega). \tag{5}$$

The signal $g(t)$ can be recovered by

$$\hat{x}(t) = (w \star g)(t) \tag{6}$$

with a Wiener Filter as

$$W(\Omega) = \frac{H^*(\Omega)S_x(\Omega)}{|H(\Omega)|^2 S_x(\Omega) + S_n(\Omega)}, \tag{7}$$

where $W(\Omega)$ is the Fourier transform of the Wiener filter, $H(\Omega)$ is the Fourier transform of $h(t)$, $S_x(\Omega)$ and $S_n(\Omega)$ are the power spectral densities of $x(t)$ and $n(t)$, and the superscript * indicates complex conjugation.

To adapt the Wiener filter to our context, we must assume time-invariance, i.e. $a(t) = \alpha$ is constant in (2) and so we rewrite (4) as

$$g(t) = \alpha (\delta \star x)(t) + n(t), \tag{8}$$

where we use the convolution of the impulse function $\delta(t)$ with the signal $x(t)$ to have a time-invariant equivalence to (2).

As $x(t)$ is a sum of shifted echo prototypes $S_x(\Omega)$ can be written as $MS_f(\Omega)$ and the Wiener filter now is given by

$$W(\Omega) = \frac{\alpha M S_f(\Omega)}{\alpha^2 M S_f(\Omega) + \sigma^2}, \tag{9}$$

where $S_f(\Omega)$ is the power spectral density of the echo prototype $f(t)$, M is the number of shifted echoes and σ^2 is the noise variance.

On the other hand, TCG aims to correct the attenuation only

$$\hat{x}(t) = \frac{g(t)}{a(t)}. \tag{10}$$

As it can be seen, the amplification is directly proportional to the modeled attenuation. As classical TCG neglects noise, the resulting signal $\hat{x}(t)$ will be noisier as t increases making it harder to detect an echo.

IV. Adaptive TCG

As in a typical ultrasound signal the SNR varies with time, a single Wiener filter is not sufficient nor suitable for the entire signal. Therefore, we define a set of Wiener filters, each one valid only for a specific time instant, as

$$W_\tau(\Omega) = \frac{a_\tau M S_f(\Omega)}{a_\tau^2 M S_f(\Omega) + \sigma^2}, \tag{11}$$

where $a_\tau = a(\tau)$ was re-purposed. In other words, $W_\tau(\Omega)$ is valid only for $\tau = t$.

Filtering the observed signal through each filter of (11) yields a set of signals given by

$$z_\tau(t) = (w_\tau \star g)(t). \tag{12}$$

The final estimate is obtained by (diagonally) collecting the outputs from the Wiener filters only at their respective valid instant and assembling a single signal as

$$\hat{x}(t) = z_\tau(t)|_{\tau=t}. \tag{13}$$

One may argue that this result is valid only if the phase of $W_\tau(\Omega)$ is equal for all τ, so as we can coherently combine their outputs. We shall prove next that not only this is true, but $W_\tau(\Omega)$ are zero-phase filters for all τ.

Proof: In (7), as the terms $S_x(\Omega)$, $|H(\Omega)|^2$ and σ^2 are real-valued, only $H^*(\Omega)$ contributes to the phase. In the proposed Adaptive TCG, this term is replaced by $a_\tau M$, which is also real-valued. As all terms in (11) are real-valued, $W_\tau(\Omega)$ is zero-phase for all τ.

V. Results

A. Simulations

Figure 1 illustrates the advantage of the proposed method over TCG and Wiener filter. We simulated 5 echoes of a 5 MHz transducer in a hypothetical medium with $\beta_m = 4 \times 10^5$ and with noise added to a SNR of 15 dB. The first two echoes are clearly visible, whereas the last two are totally covered by noise. The middle echo is somewhere in-between. Differently from other techniques, the proposed method handles jointly the presence of noise and spatial attenuation.

In Table I, we present the SNR improvement provided by the proposed method for different scenarios. The SNR improvement is calculated by

$$\text{ISNR} = \text{SNR}(x(t), \hat{x}(t) - x(t)) - \text{SNR}(x(t), n(t)) \tag{14}$$

The same 5 echoes were considered, but the rows represent different values of β_m, ranging from a low-attenuation medium (like carbon steel) to a high-attenuation medium (like stainless steel), whereas the columns account for different levels of noise. Results were obtained over 1000 runs.

As it can be seen, the improvement in the SNR is higher for high levels of noise. For highly dispersive media, the echoes are very attenuated and become dominated by noise. Improvement in SNR is not possible, leading to negative values in the table.

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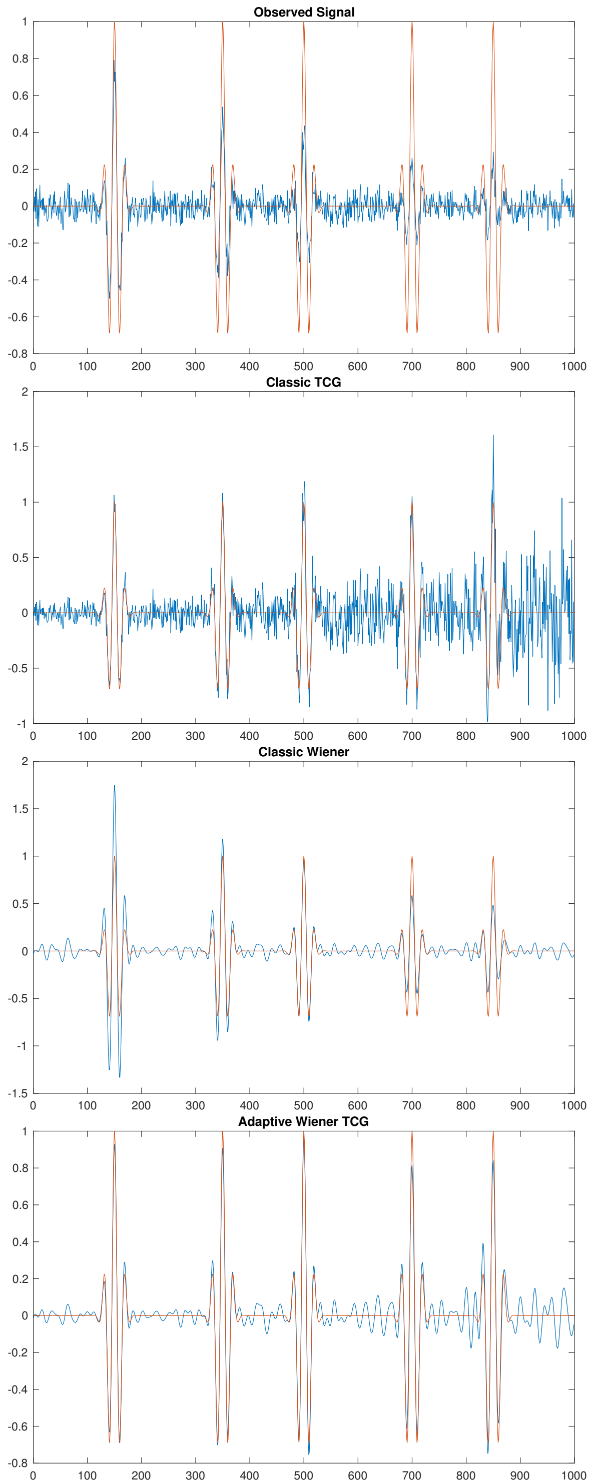

Fig. 1. Visual comparison of simulation results for Classical TCG, Wiener filter and the proposed Adaptive TCG. The signal in red is the original signal and the best reconstruction possible. The observed signal is degraded with noise, classical TCG applies an amplitude gain to correct the echoes amplitude but it also increases noise in the same degree. Wiener filtering aims to reduce noise but it does not correct the amplitudes of the echoes. The proposed method applies an adaptive gain that corrects the amplitudes of the echoes and also reduces noise.

TABLE I
SNR IMPROVEMENT (ISNR) FOR DIFFERENT COMBINATIONS OF ATTENUATION AND NOISE LEVEL.

$\beta \times 10^5 \backslash$ SNR (dB)	10	20	30	40
1.0	7.08	6.22	5.40	4.69
1.5	4.48	3.33	2.72	2.00
2.0	2.08	0.58	-0.22	-0.83
2.5	-0.35	-2.22	-3.36	-4.02

B. Experimental Results

The experimental validation of the proposed Adaptive TCG algorithm was carried out processing ultrasonic signals acquired by an ultrasonic inspection system (UIS). This UIS has several components, such as ultrasonic transducer, ultrasonic pulser/receiver and acquisition system.

The transducer is a *VideoScan V110-RM* produced by *Olympus*. Its active element has a circular shape with 6 mm of diameter and nominal frequency of 5 MHz [10], emitting mainly longitudinal ultrasonic waves. The pulser/receiver model is *5077PR* by *Panametrics*. The signal received by transducer is amplified in the pulser/receiver and it is digitalized by an acquisition system. This acquisition system—produced by *NI*—consists of a *PXIe-1078* chassis, a *PXIe-8135* controller and a *PXIe-7966R FlexRIO* controller with a *FlexRIO NI 5752* input and output module. The acquisition rate of ultrasonic signals is 50 MS/s and the digitized values have resolution of 12 bits.

For this test, the transducer was placed at a normal angle over an aluminum block, as depicted in Fig. 2. Vaseline was used to enhance coupling.

The acquired signal is composed by several echoes, generated by multiple reflections on the bottom and top surfaces of the block. Each echo is an attenuated and shifted copy of the original pulse. Thus, we are able to assess the performance of the algorithms at different distances.

Figure 3 presents a visual comparison for the results of classical TCG, Wiener filter and the proposed Adaptive TCG. Whereas TCG yields noise amplification at the end of sequence and Wiener filter does not correct spatial attenuation, the proposed method is able to deliver attenuation correction while controlling noise amplification.

VI. CONCLUSION

In this paper, we presented an Adaptive Time Correction Gain based on a time-varying Wiener filter. The proposed Adaptive TCG is able to handle jointly the noise and the correction of the spatial attenuation.

To achieve this goal, we derived a time-varying Wiener deconvolution by first defining a set of time-invariant Wiener filter, where each filter of the set was “valid” only for a specific time instant, i.e. the moment when spatial attenuation was expected to reach a certain level.

As all filters were zero-phase, we were able to diagonally combine their outputs to assemble a single signal as the final estimate of the Adaptive TCG.

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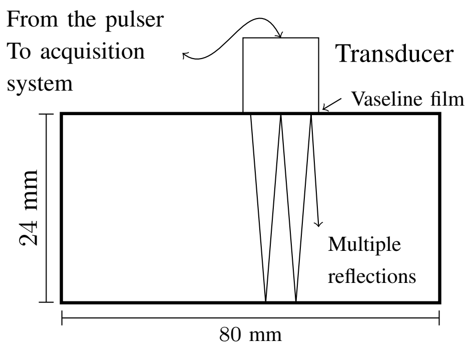

Fig. 2. Depiction of the experimental setup. Due to multiple reflections of the ultrasound wave in the aluminum block, the excitation burst is received by the transducer as several echoes. Subsequent echoes have smaller amplitudes, which are inversely proportional to the distance traveled by the ultrasound beam.

We presented simulation and experimental results for visual and quantitative appreciation of the proposed method. Future work includes a theoretical error analysis to support the results (e.g. Table I) as well as evaluation of improvements provided by the Adaptive TCG as preprocessing for more sophisticated reconstructions algorithms such as [2].

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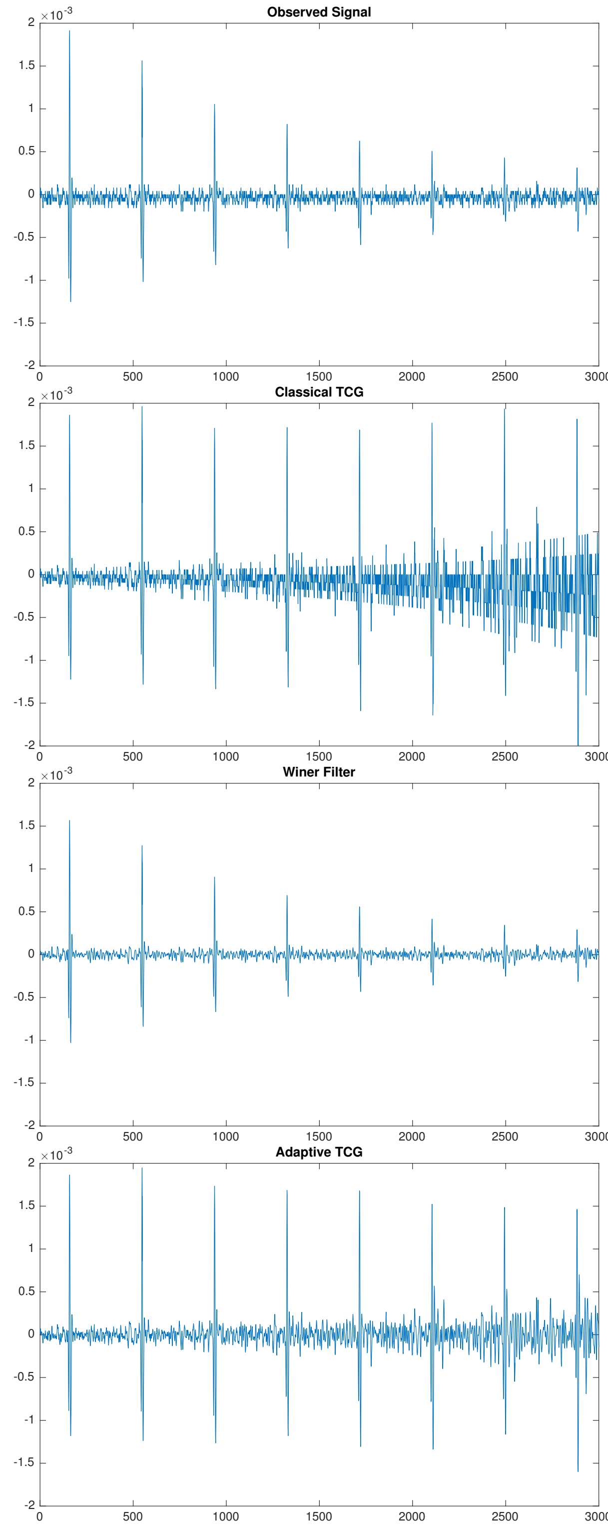

Fig. 3. Experimental results for Classical TCG, Wiener filter and the proposed Adaptive TCG. The proposed method was capable of correcting the amplitudes of the echoes and increasing SNR at the same time.