Improving Time Estimation by Blind Deconvolution: with Applications to TOFD and Backscatter Sizing

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Outline

• Introduction
• Deconvolution and Blind Deconvolution
• Wavelet Estimation by Kurtosis Maximization
  – The why and how it works
• From the white reflectivity to spectral widening
  – Autoregressive spectral extrapolation
• Examples
  – Synthetic and real examples in TOFD and Backscatter signals
• Conclusions
The problem (convolutional model)

\[ s(t) = w(t) \ast r(t) + \eta(t) \]

- \( r(t) \) – medium reflectivity
- \( w(t) \) – wavelet
- \( \eta(t) \) – noise
- \( s(t) \) – observation
- \( r_e(t) \) – estimated

Blind deconvolution
\( s(t) \) - Only observation is known
\( w(t) \) - ? -- \( r(t) \) - ?
The problem (convolutional model)

- A wavelet is a ‘small wave’
- It is a pulse-like waveform.
- The dreamed wavelet: A Dirac delta function.
  - Physical reasons limiting these dreams
    - Sources of generation
      - Dynamite (Seismic)
      - Air guns (Offshore seismic)
      - PZT (UT)
Wavelet Estimation and Deconvolution

• Objective:
  – Can we extract the reflectivity without prior knowledge about the wavelet?

• Possible applications:
  – Weak diffracted signals: TOFD and backscattered signals.
  – Deconvolution and localized decon – time resolution

• Main problem
  – Extracting the reference wavelet:
    • It is time (depth) dependent, angle dependent, user dependent (subjective task)

We provide a fully blind deconvolution framework
Wavelet estimation

How many eligible wavelets are there?

\[ s(t) = w(t) \ast r(t) \]
\[ S(Z) = W(Z)R(Z) \]

\[ S(Z) = s_0 + s_1Z^1 + \ldots + s_nZ^n \]

\[ S(Z) = s_m \prod_{k=1}^{m} (Z - Z_k) = w_n \prod_{k=1}^{n} (Z - Z_k) \cdot r_{m-n} \prod_{k=1}^{m} (Z - Z_k) \]

Possible solutions

\[ m = 3000; \% \text{ length}(s(t)) \]
\[ n = 100; \% \text{ length}(w(t)) \]

How to find the \( n \) roots of the wavelet, from the \( m \) roots of the seismogram? Combinatorial problem!!!

\[ \text{Possible solutions} \]

\[ N_w = \frac{m!}{n!(m-n)!} \]

\[ N_w = 10^{200} \]

The white reflectivity assumption

\[ s(t) = w(t) \ast r(t) + \eta(t) \]
Wavelet $w(t)$ is the propagating UT pulse

\[ F(f) = W^{-1}(f) \]
\[ |F(f)| = \frac{1}{|W(f)|} \]
\[ \phi_f(f) = -\phi_w(f) \]

If we find the proper Inverse filter, the wavelet should become ZERO-PHASE after deconvolution.
Deconvolution in the Fourier domain

\[ s(t) = w(t) \ast r(t) + \eta(t) \quad \text{FT} \quad S(f) = W(f)R(f) + N(f) \]

Simple inverse filter

\[ R_{est}(f) = W^{-1}(f)R(f) - W^{-1}(f)N(f) \]

where \( H(f) \rightarrow \text{zero}, \) \( N \rightarrow \infty \)
leading to incorrect estimates

\[ R_{est}(f) = \frac{S(f)W^*(f)}{|W(f)|^2 + Q^2} \]

\( Q^2 \) – noise desensitizing factor

\[ Q^2 = \max(|W(f)|^2)/100, \]

- Damping Factor
- Water level
- Regularization parameter

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What we have so far?

• We need a wavelet
• The reflectivity is white – Why? Good question!
  \[ |S(f)| = \sigma |W(f)| \]

What else we need?

• Deconvolve to get a zero-phase wavelet
• Spectral broadening or whitening by autoregressive spectral extrapolation
Wavelet estimation

Deterministic approaches

- Take a representative part of the trace
  - Backwall reflector (Honarvar et al., 2004)
  - Lateral wave

Create a dictionary of wavelet for different conditions.

Statistical Methods

- Homomorphic deconvolution (Ulrych, 1971)
- Bicepstrum (Herrera et al., 2006)
- Short-time homomorphic wavelet estimation (Herrera and van der Baan, 2012)
- Kurtosis-based wavelet estimation (Van der Baan, 2008)

Reflections with shapes that differ from the preselected reflector will be misrepresented.
Wavelet estimation by Kurtosis Maximization

- Convolving any white reflectivity with an arbitrary wavelet renders the outcome less white, but also more Gaussian.

- Since kurtosis measures the deviation from Gaussianity, we can recover the original reflectivity by maximizing the kurtosis

\[
\kappa[s] = \frac{E[s^4]}{(E[s^2])^2} - 3,
\]

\[
W_{est}(f) = |S_{cc}(f)| \exp\{i \phi_{\text{kurt}} \text{sgn}(f)\}
\]

Constant phase rotation of the observed ultrasound trace.

\[
s_{rot}(t) = s(t) \cos \Phi + H[s(t)] \sin \Phi
\]
Examples

TOFD

Backscatter signal

Synthetic reflectivity

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Convolutional model in action

Wavelet – $w(t)$

Reflectivity – $r(t)$

Signal – $s(t)$

$+ \eta(t) \rightarrow 15 \text{ dB}$

$s(t) = w(t) * r(t) + \eta(t)$
Wiener filtering + ASE

Original reflectivity – $r(t)$

Deconvolved Wiener filtered – $rw_{est}(t)$

Estimated reflectivity $r_{est}(t)$

Wiener filter + Autoregressive Spectral Extrapolation
Final deconvolution stage

Original Noisy Signal – $s(t)$

Deconvolved Wiener filtered – $rw_{est}(t)$

Estimated reflectivity - $r_{est}(t)$
Spectrum estimation

Original Noisy Signal – $s(t)$

Deconvolved Wiener filtered – $rw_{est}(t)$

Estimated reflectivity - $r_{est}(t)$

Original reflectivity - $r(t)$

Extrapolating the green spectrum leads to the estimated reflectivity spectrum

Actual reflectivity spectrum

Estimated reflectivity spectrum
Real data examples

Deconvolution of TOFD dataset

- dataset acquired using the UTScan system
- $fs = 100 \text{ MS/s}$
- TOFD with 5 MHz probes
- 10.8” pipe of 17.5 mm of thickness

- 862 A-Scans
- Estimate 1 wavelet per trace

Next →

- Parallel processing (1 A-scan per core)
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Deconvolution of A-Scan 120

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Deconvolution of TOFD dataset

[Graphs showing input data and deconvolved data with A-scans and time in microseconds]
Deconvolution of back diffraction dataset

Phased array inspection → surface breaking flaw
- S-Scan

Figure 2-46 RF display of the crack tip by direct and skip beam.

From Olympus book- Intro to phased arrays
Page 79.


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Deconvolution of back diffraction dataset

Original (blue) and Deconvolved for Shot: 15 Angle 48.2

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Deconvolution of back diffraction dataset

A-Scan 15

Deconvolved A-Scan 15

Envelope A-Scan 15

Hilbert T

Raw signal Shot: 15 Angle 48.2

Deconvolved for Shot: 15 Angle 48.2

Envelope of the Deconvolved signal for Shot: 15 Angle 48.2
Conclusions

• Constant phase wavelet estimation
  – good results in isotropic media (wavelet changes are mainly due to amplitude attenuation with almost constant frequency) → For strong frequency variations then use short-time homomorphic wavelet estimation method STHWE.

• One wavelet per trace or One wavelet per section
  – Computational cost and real time implementation.
  – Autoregressive spectral extrapolation

• The deconvolution step can be integrated into the TOFD and S-Scan methods. Its implementation could be easily parallelized.
Conclusions

• Time variant implementation
  – For example we can divide a TOFD dataset into three zones: lateral wave, center and backwall. We can then perform the blind deconvolution method and join the deconvolved sections.

• Regarding the phase information:
  – Further work is needed to use the phase information provided by the deconvolution method in both techniques (TOFD and back diffraction).
Future work

Statistical wavelet estimation

+ Sparse deconvolution
Thank you for your attention

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