Ultrasound Imaging for Quantitative Measurement of Immersed Plastic Waste Particles

Seyed Ali Sanaee and Maarten C.M. Bakker

Resources & Recycling Group, Delft University of Technology, the Netherlands
Background: Magnetic Density Separation

The magnet creates a mass density gradient in the ferrofluid.

- Particles separate even for small differences in mass density.
- Complication: the ferrofluid is opaque.
Research Field

Ultrasound Sensor Array Techniques For:

- Monitoring the Separation Process
- Quality Inspection
- Throughput measurement
Research Objective

A **FIXED** Linear Sensor Array

The Challenge

**Volumetric Throughput** ↔ **Advanced Imaging Techniques**
Wave Field Redatuming + SAFT

(1) 2D FFT
\[ g(x, y_0 = 0, t) \Rightarrow G(k_x, y_0 = 0, \omega) \]

(2) Back propagation
\[ G(k_x, y, \omega) = G(k_x, y_0 = 0, \omega) \exp(ik_y y) \]

(3) 2D IFFT
\[ g(x, y_P, t) = \int \int G(k_x, y_P, \omega) \exp(ik_x x) \exp(i\omega t) dk_x d\omega \]

(4) SAFT Kernel
\[ S_{SAFT}(t) = \sum_{n=1}^{N} g(x_{P,n}, y_{P,n}, t - \Delta t_n) \]
Phase Shift Migration

Horizontally layered medium

\[ \hat{G}(k_x, y_N, \omega) = \hat{G}(k_x, y_{N-1}, \omega) \exp(ik_{y;N}(y_N - y_{N-1})) \]

\[ k_{y;N} = \sqrt{\left(\frac{\omega}{c_N}\right)^2 - k_x^2} \]

\[ \hat{G}(k_x, y, \omega) = \hat{G}(k_x, y_{N-1}, \omega) \exp(ik_{y;N}(y - y_{N-1})) \]

\[ G(x, y, t = 0) = \int \int \hat{G}(k_x, y, \omega) d\omega \exp(ik_x x) dk_x \]
Non-stationary Phase Shift Migration

Generalized form of PSPI:

\[ \hat{G}(x, y, \omega) = \int \hat{G}(k_x, y_0, \omega) \exp(i k_y (y - y_0)) \exp(i k_x x) dk_x, \]

Or written as a windowing operation:

\[ w_N(x) = \begin{cases} 1, & c_N = c(x) \\ 0, & c_N \neq c(x) \end{cases} \]

\[ \hat{G}(x, y, \omega) = \sum_{n=1}^{N} w_n(x) \text{ IFFT}[\hat{G}_{c,n}(k_x, y, \omega)] \]
Collecting data

- **Ultimo Pulser**
  - linear array 128 elements
  - 5 MHz

- **Matrix Switch**
  - 1 2 3 4 ............... 127 128

- **LAN Interface**
- **AD Board**
- **PC**

**NOT real-time (Hardware Limitation)**
The generic test particle

Wide range of refraction angles

$c_{\text{Water}} = 1480 \text{ m/s}$

$\begin{cases} c_p = 2341 \text{ m/s} \\ c_s = 1060 \text{ m/s} \end{cases}$

Generic case study for polyolefin waste particles

Water

Polymer

Depth [mm]

0.01

0.015

0.02

0.025

0.03

Width [mm]

0

0.01

0.02

0.03

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Information in different Data-sets

(4, 5): PCSP, PSCP

Example: PE dataset

<table>
<thead>
<tr>
<th></th>
<th>Hit-rate</th>
<th>Coverage</th>
<th>Amplitude</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCCP</td>
<td>1</td>
<td>89%</td>
<td>down to -2 dB</td>
<td>Uniform</td>
</tr>
<tr>
<td>PSSP</td>
<td>2</td>
<td>67%</td>
<td>down to -90 dB</td>
<td>Localized</td>
</tr>
</tbody>
</table>
Imaging Performance - 1

Critical reflection at the front surface shields the back

Redatuming, PE
Redatuming, PW
NSPS, PE
NSPS, PW
Imaging Performance - 2

Again, data missing due to critical reflection

Enlarge the viewing aperture
Follow up research

Double Arrays

✓ Overcomes the critical reflection angles
✓ Full illumination of the front and back surface
Sampling and measurement error in Online Ultrasound

Average M batches:

\[ V_{\text{measurement}} = \frac{1}{M} \sum_{m=1}^{M} \sum_{n=1}^{N} lw(d_n + \Delta d) = \bar{V}_{\text{sample}} + lw\sqrt{N / M} \sigma_{\text{imaging}} \]

\[ E_{\text{sampling}} = 1 / \sqrt{MN} \]
\[ E_{\text{measurement}} = \sqrt{N / M} \sigma_{\text{imaging}} \]

Imaging Accuracy ↔ Measurement Speed
Summary & Conclusions

- Developed are ultrasound imaging techniques dedicated to measuring plastic waste particles
- Only PCCP rays prove suitable for back surface imaging
- Back surface may be hidden by critical reflection at the front side: a double sensor-array may resolve this
- Good imaging accuracy is required to achieve fast measurements in an online MDS set-up with fixed-view probes (no possibility for constant view adjustments)