Iterative Learning Control of a Marine Vibrator

Bo Bernhardsson, Olof Sörnmo, Per Gunnarsson, Olle Kröling, Rune Tengham
Marine Seismic Surveys
Outline

1. Seismic surveying
2. Acoustic Sources
3. System Identification
4. ILC
5. Results for different sensors
How to do seismic surveying:

- Generate a HUGE acoustic signal
- Pick up echoes using a HUGE (kilometers) sensor array
- Do some signal processing (correlation analysis)
Marine Seismic Surveys
Output from seismic survey

Higher frequencies -> Great resolution near surface structure
Lower frequency -> Better characterization of structure at depth
Spectrum Requirements

Want to minimize impact on
  - endangered marine species
  - commercial fishing

Promote greener alternatives

Reduce high-frequency spectral contents of acoustic signal

Example of specification: Harmonics above 100 Hz should be attenuated 40 dB
Acoustic Sources

Air guns have traditionally dominated the market

Higher peak pressures than most other man-made sources, except explosives

New novel constructions have the potential for reduced "acoustic footprints"
Reduce peak pressures

Chirp signals give smaller peak pressures than airguns.
Challenges due to the Law of Physics

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Amplitude</th>
<th>Input Power</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000 Hz</td>
<td>0.0004 mm</td>
<td>270.4 W</td>
<td>99.9 %</td>
</tr>
<tr>
<td>1,000 Hz</td>
<td>0.0052 mm</td>
<td>416 W</td>
<td>66 %</td>
</tr>
<tr>
<td>100 Hz</td>
<td>0.45 mm</td>
<td>3.6 kW</td>
<td>7.4 %</td>
</tr>
<tr>
<td>60 Hz</td>
<td>1.3 mm</td>
<td>6.5 kW</td>
<td>4.4 %</td>
</tr>
<tr>
<td>30 Hz</td>
<td>5 mm</td>
<td>12 kW</td>
<td>2.2 %</td>
</tr>
<tr>
<td>10 Hz</td>
<td>45 mm</td>
<td>36 kW</td>
<td>0.074 %</td>
</tr>
</tbody>
</table>

PISTON GENERATING 195 dB

Radiation from a Piston with Radius 0.3 m and a Source Level of 195 dB
Design Challenges with Marine Vibrators

Want

- High output power
- High efficiency (for used frequencies)
- Exact acoustic signals (linearity, repeatability)

Instead of airguns: Electro-mechanical constructions with well designed useful mechanical resonances

Problems: Backlash, friction, saturation effects, ...
The Control Problem

Input:
- Voltage or current to coils

Possible measurement sensors:
- Accelerometer(s) on shell of vibrator
- Accelerometer(s) on moving parts inside vibrator
- Microphones inside vibrator
Experiments indicate that the imperfections generate very repeatable errors

Good candidate for iterative learning control (ILC)

Very satisfactory results with ILC
Before ILC

Input signal before ILC

Output signal before ILC
After ILC
System identification

Dynamics can vary due to aging, temperature etc
Want to minimize time for calibration/system identification
Both SISO and MIMO operation is feasible
Small-signal response around nominal trajectory

Excitation signal

\[ u(t) = u_0(t) + C \sin 2\pi f_k t \]

for \( f_k = [20, 1000] \) Hz.

Important to use a nonzero \( u_0(t) \) to overcome friction etc.

Two separate inputs to coils. Several sensors can be used.

SISO vs MIMO models. Choose \( 2 \times 2 \) model

\[
\begin{bmatrix}
G_{11} & G_{12} \\
G_{21} & G_{22}
\end{bmatrix}
\]
Many resonances. Very high system order.

Decided to do ILC in the frequency domain
ILC algorithm, FFT-based

Wanted reference chosen as either

- \( R(f) = G(f)U(f) \), where \( U(f) = \mathcal{F}(\text{chirp}) \)
- \( R(f) = \mathcal{F}(\text{chirp}) \)

\[
 u_{k+1}(f) = Q_2(f)u_k(f) + Q(f)G^{-1}(f)(R(f) - Y(f))
\]

Filters chosen as

\[
 Q(f) = \begin{cases} 
 0.1 - 0.5 & \text{for frequencies we want the ILC to be active} \\
 0 & \text{otherwise}
\end{cases}
\]

\( Q_2(f) = 1 \)

Note: \( G^{-1} \) matrix inverse in the \( 2 \times 2 \) case
Convergence SISO
Robustness experiment - abrupt gain change

Gain change at iteration 16

Convergence in 15 iterations
Spectrum after ILC - spring sensor

43-60dB suppression of harmonics

ILC active to 1kHz
Active ILC in 30-1000Hz, $Q=0.3$ 15 iterations, $Q=0.15$, 30 iterations
40dB improvement in error spectrum
Spectrogram before ILC - spring sensor
Spectrogram after ILC - spring sensor
Same but with shell sensor

Very good results
Detailed view

Detailed view, rescaled color range: 70dB.
A Setback

When measuring the spectrum on the side without ILC sensor it was found that the spectrum had NOT improved very much on that side!
Double-sided control

Idea: Make both sides move sinusoidally, use separate control of the two springs

MIMO control needed
Transfer functions - 2 shell sensors

Strong cross-coupling for certain frequencies
Need matrix inversion, two separate ILCs will not work.
Spectrograms after ILC - double shell sensor

Output spectra on the shells (ILC active in [30,650] Hz)

>40dB suppression

Note: Reference = constant amplitude chirp
Spectrograms after ILC - double shell sensor

Spectrum on the accelerometers on the two sides

Both sides move according to wanted reference

40dB suppression
Convergence - double shell sensors
Spectrogram - double shell sensors (50dB range!)
Adaptation and robustifications

Several patent applications on adaptation and robustifications

Will not talk about this
Summary

- Spectrum requirements on marine vibrators motivate novel constructions and use of control
- Experiments with ILC show promising results
- Good mechanical design is still crucial

Future work
- Further testing in water is needed
- Further optimization might improve the results
Thanks to Rune Tengham at PGS for background material
Thanks to Olle Kröling and Per Gunnarsson at Subvision AB

PGS or Subvision are not responsible for any statement or opinion expressed in this presentation