Iterative Learning Control of a Marine Vibrator

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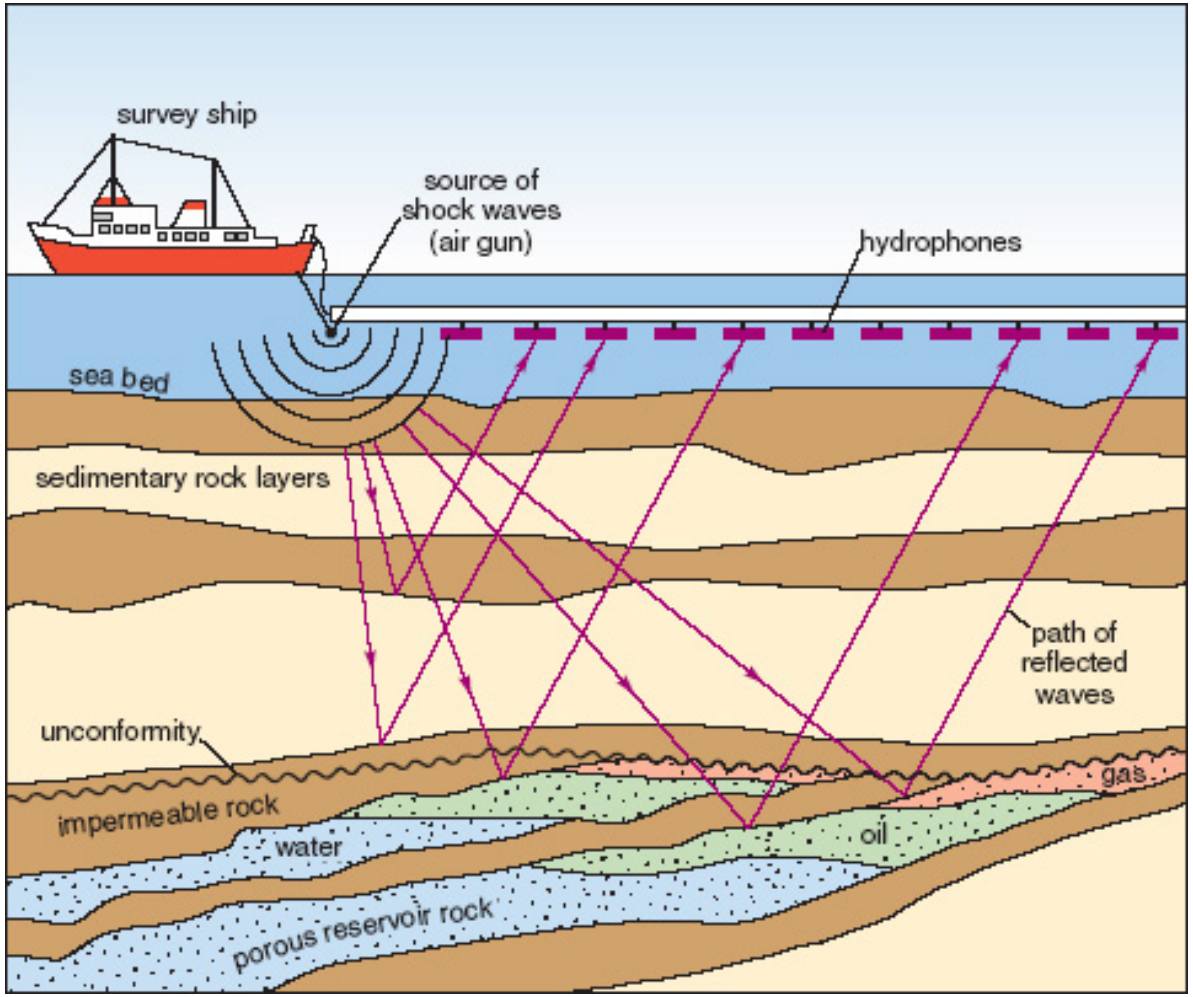
Marine Seismic Surveys



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Outline

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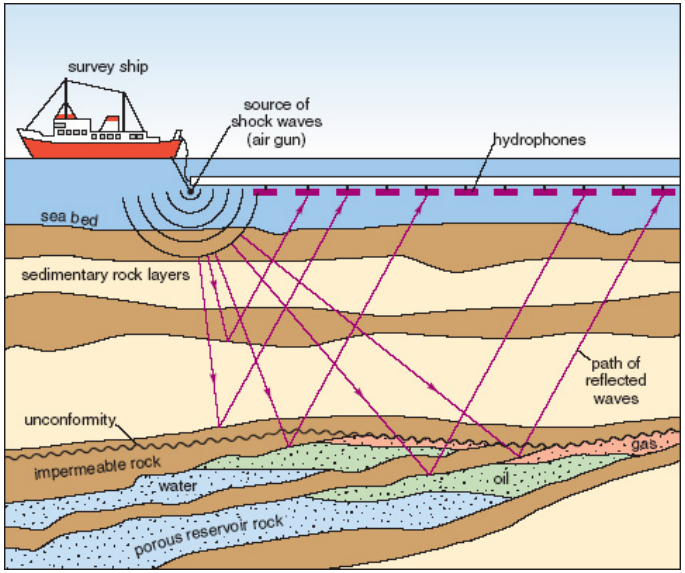
Seismic surveying



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)

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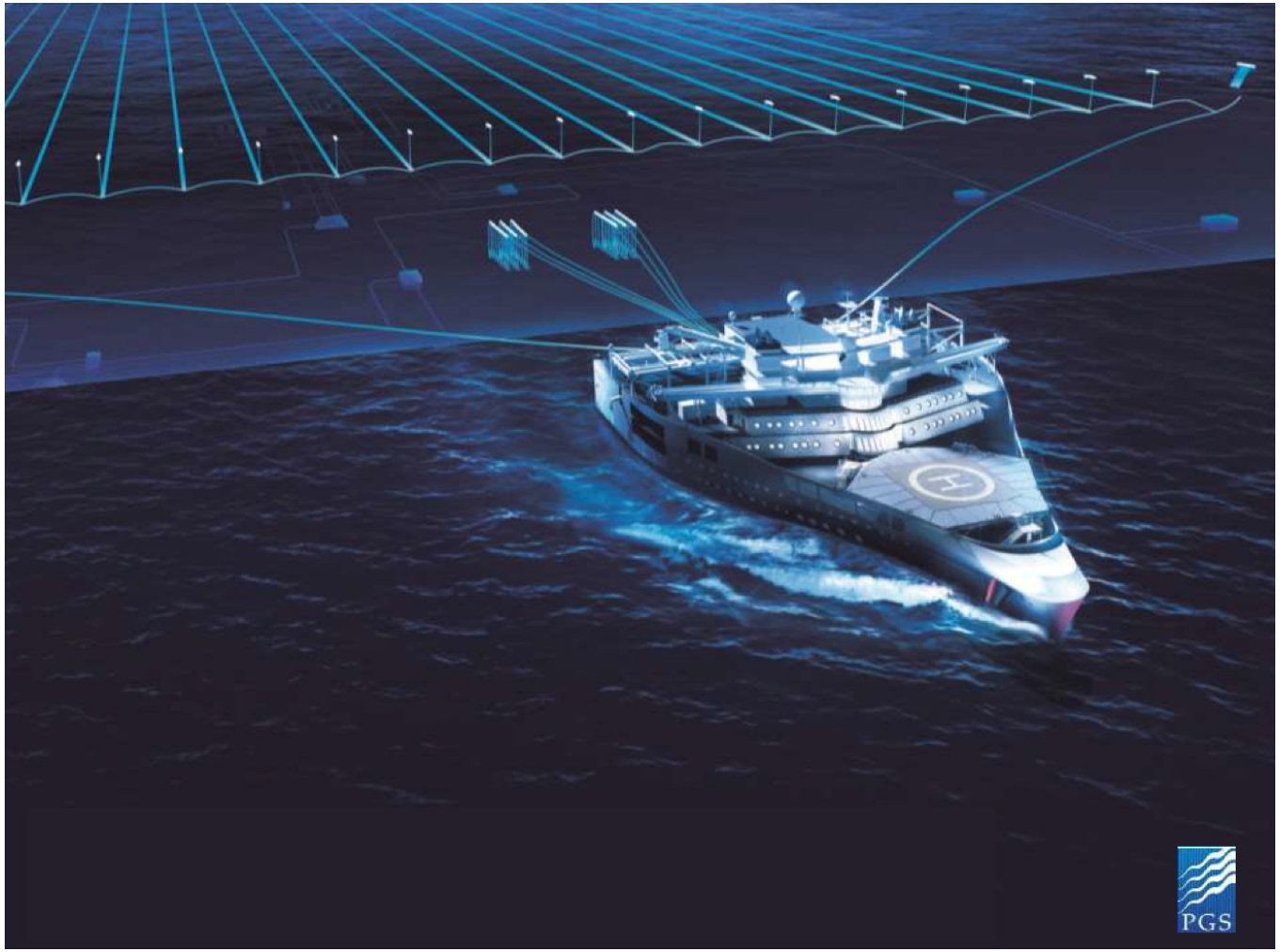
Marine Seismic Surveys



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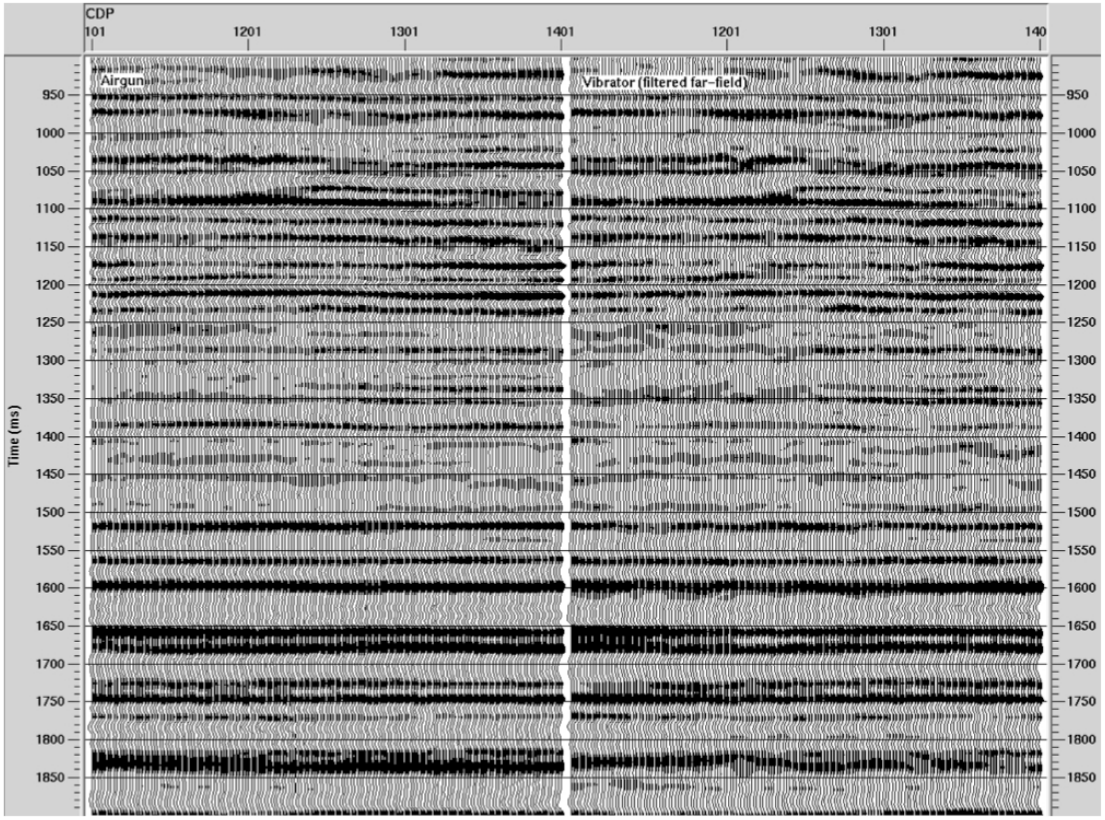
Output from seismic survey



Higher frequencies -> Great resolution near surface structure

Lower frequency -> Better characterization of structure at depth

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Spectrum Requirements

Want to minimize impact on

- endangered marine species
- commercial fishing

Promote greener alternatives

Reduce high-frequency spectral contents of acoustic signal

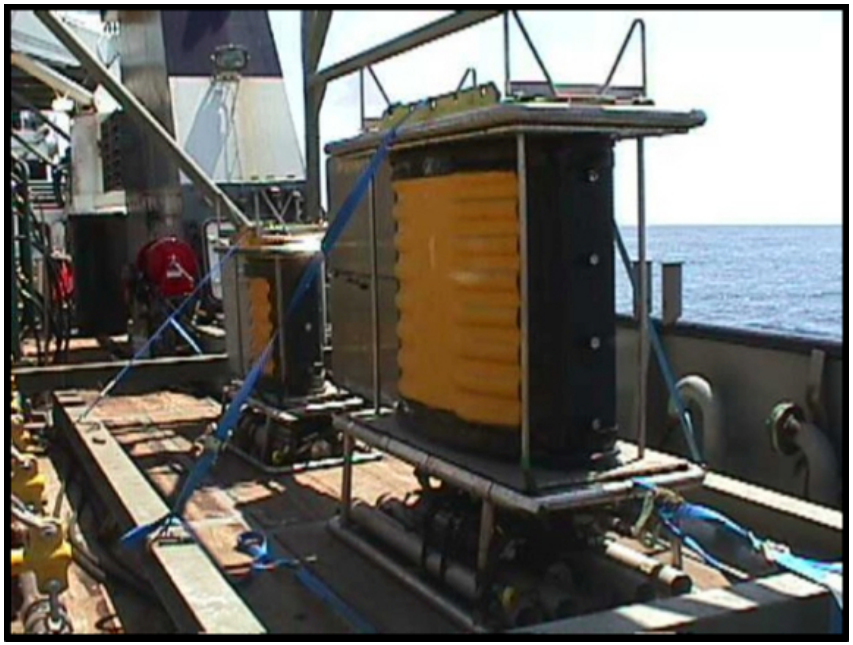
Example of specification: Harmonics above 100 Hz should be attenuated 40 dB

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"



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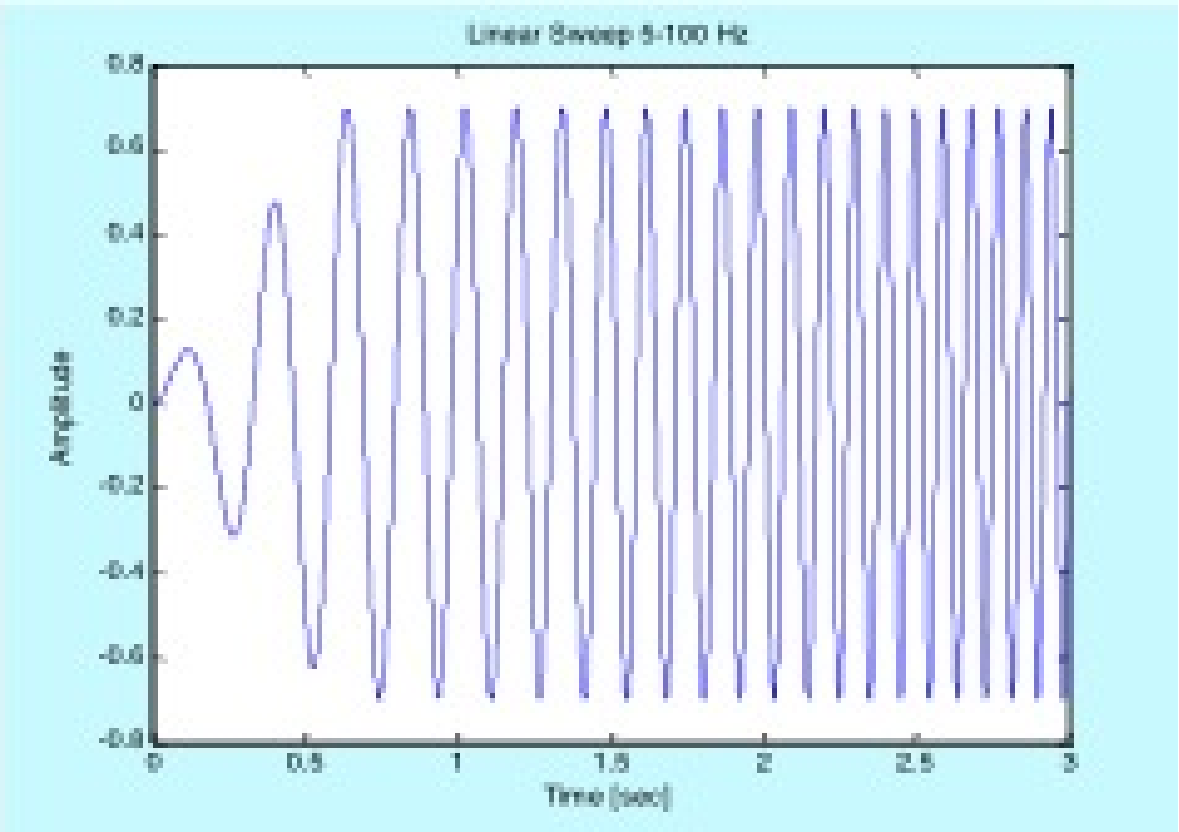
Reduce peak pressures



Chirp signals give smaller peak pressures than airguns

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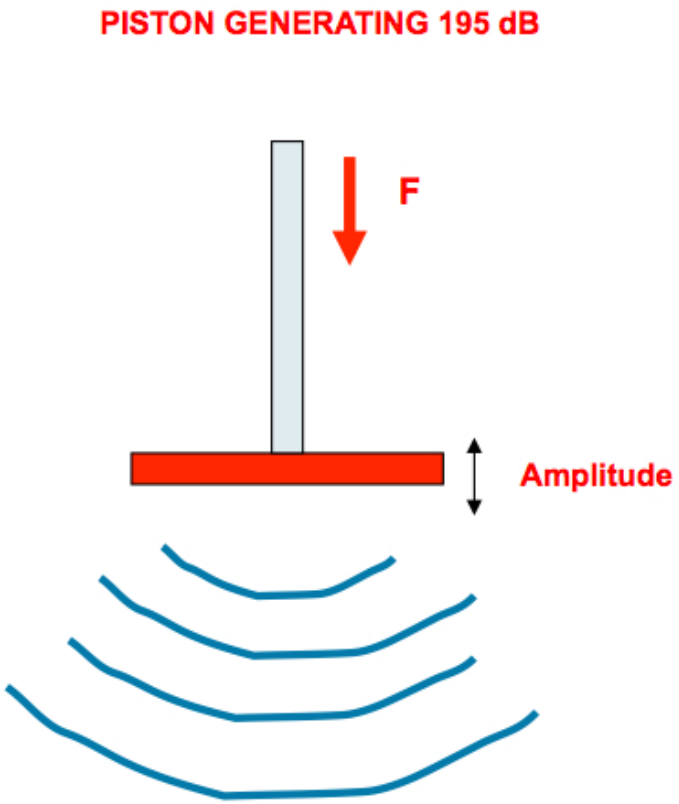
Challenges due to the Law of Physics

Frequency	Amplitude	Input Power	Efficiency
10,000 Hz	0.0004 mm	270.4 W	99.9 %
1,000 Hz	0.0052 mm	416 W	66 %
100 Hz	0.45 mm	3.6 kW	7.4 %
60 Hz	1.3 mm	6.5 kW	4.4 %
30 HZ	5 mm	12 kW	2.2 %
10 HZ	45 mm	36 kW	0.074 %



Radiation from a Piston with Radius 0.3 m and a Source Level of 195 dB

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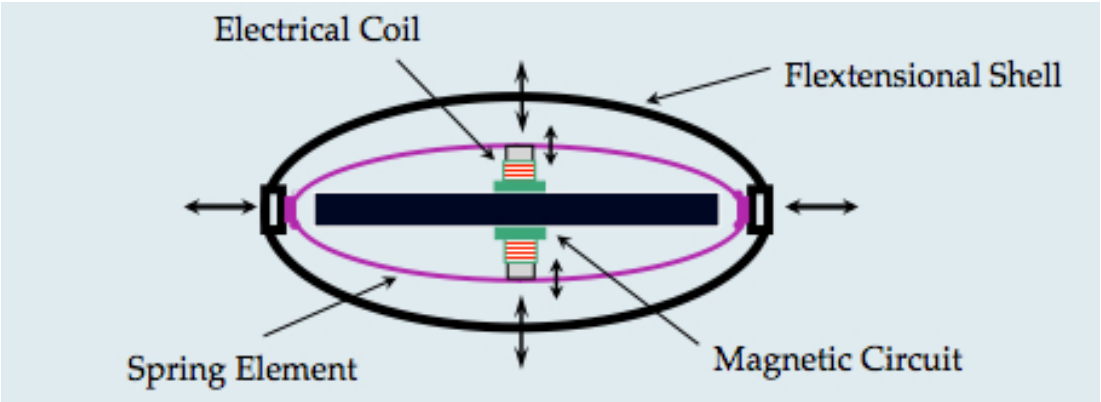
Design Challenges with Marine Vibrators

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, ...

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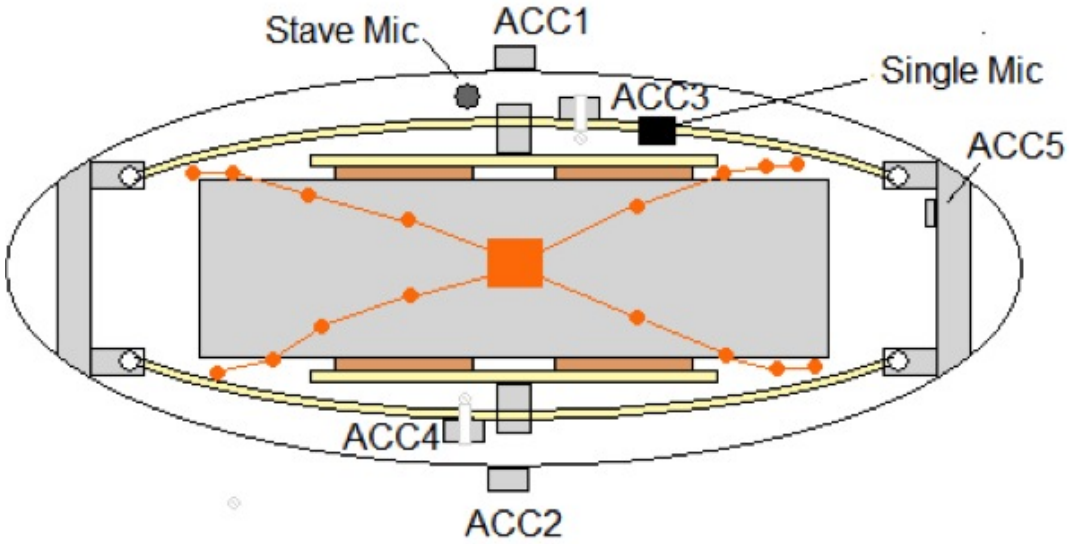
The Control Problem



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

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Repeatable imperfections

Experiments indicate that the imperfections generate very repeatable errors

Good candidate for iterative learning control (ILC)

Very satisfactory results with ILC

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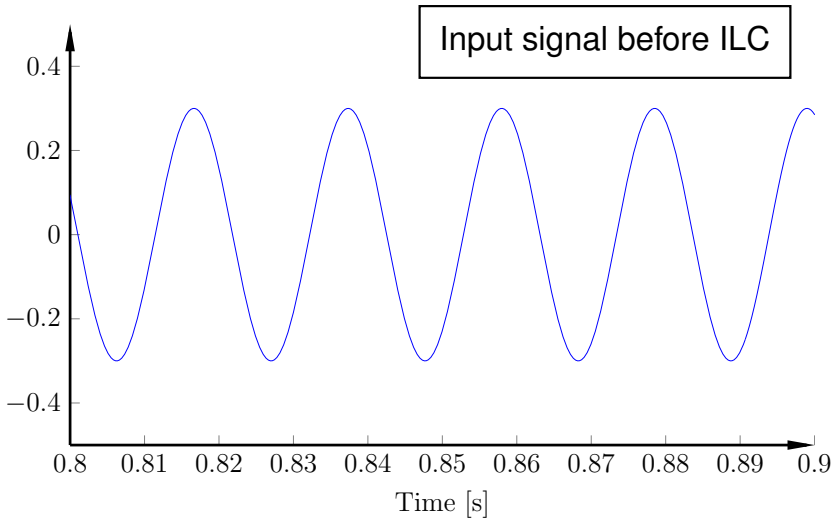
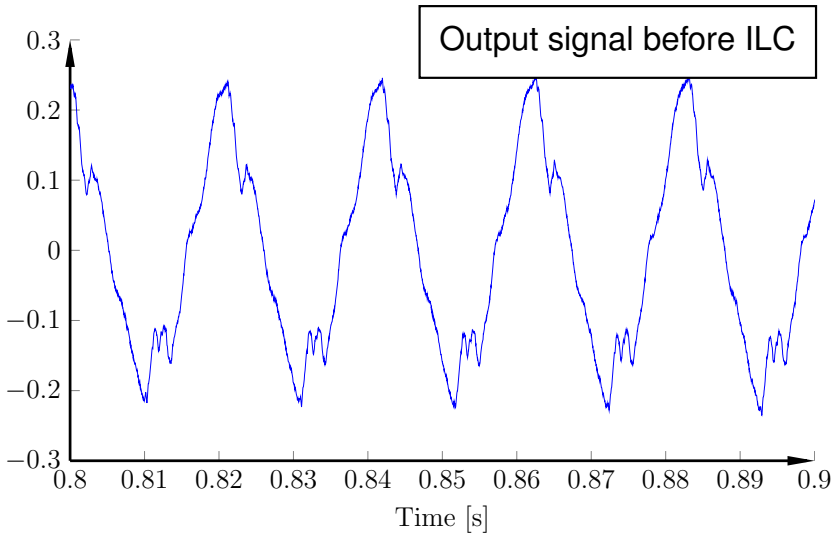
Before ILC


Input signal before ILC
0.4
0.2
0
−0.2
−0.4
0.8
0.81
0.82
0.83
0.84
0.85
0.86
0.87
0.88
0.89
0.9
Time [s]


Output signal before ILC
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0.8
0.81
0.82
0.83
0.84
0.85
0.86
0.87
0.88
0.89
0.9
Time [s]

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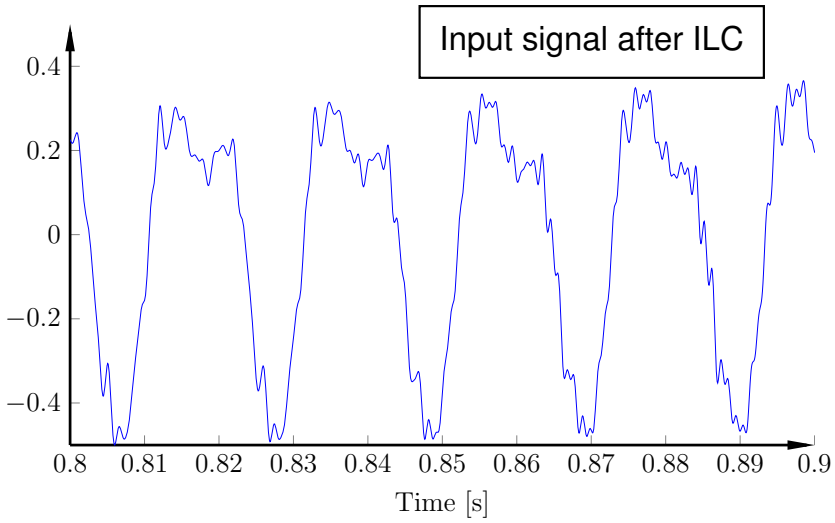
After ILC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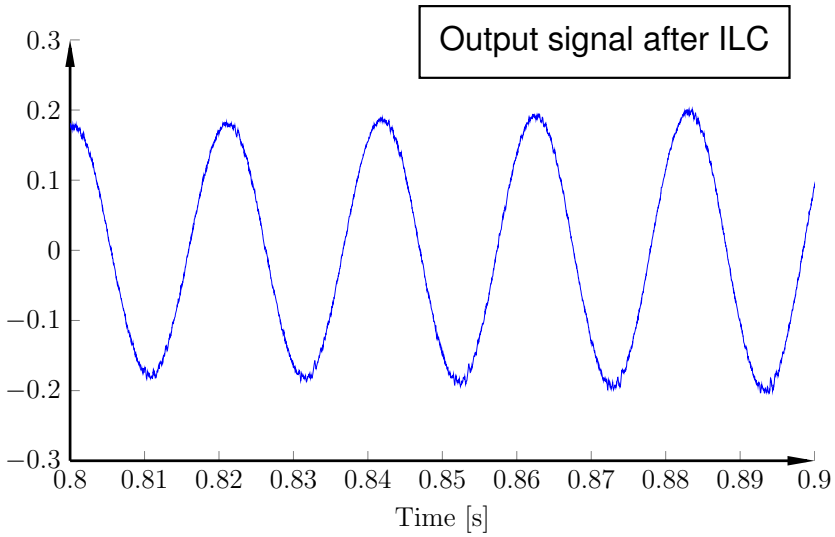
Time [s]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0.81
0.82
0.83
0.84
0.85
0.86
0.87
0.88
0.89
0.9
Time [s]

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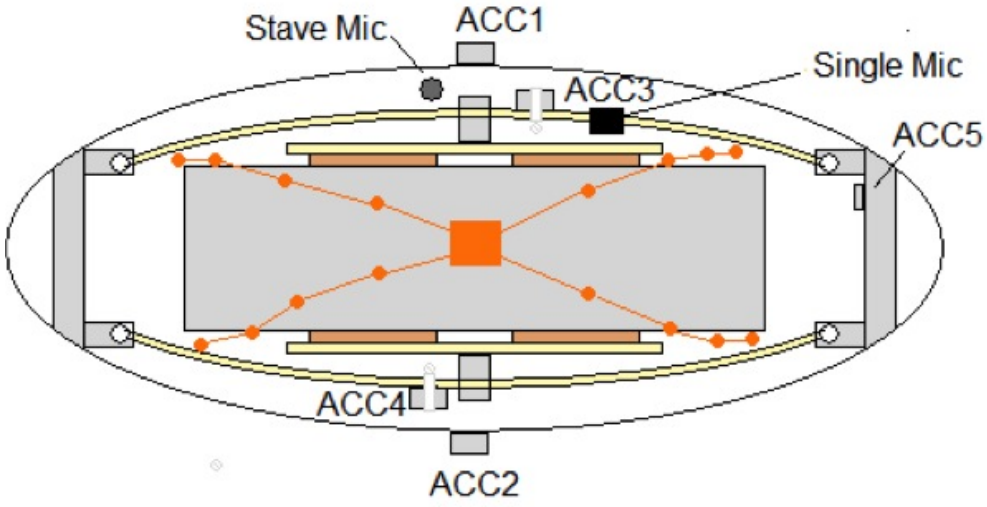
System identification



Dynamics can vary due to aging, temperature etc

Want to minimize time for calibration/system identification

Both SISO and MIMO operation is feasible

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System identification

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 2×2 model $\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}$

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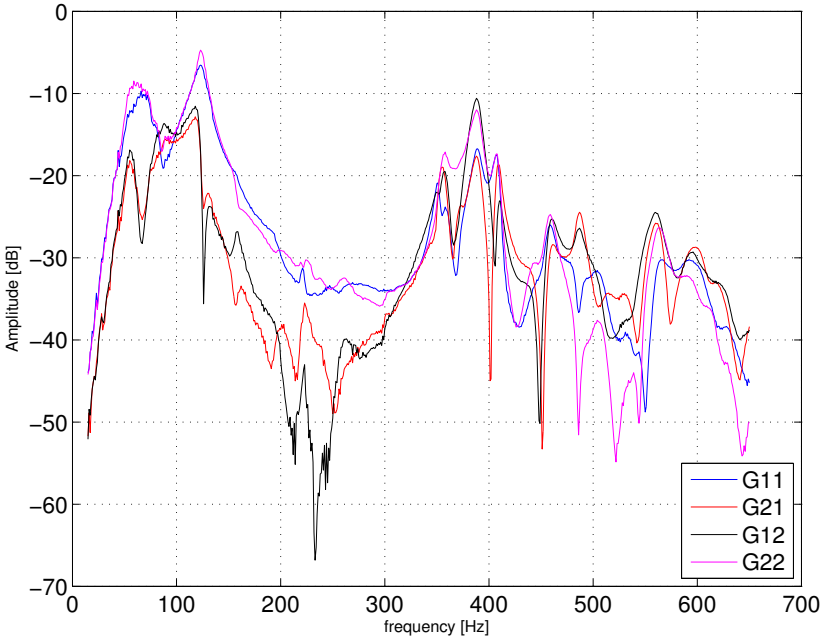
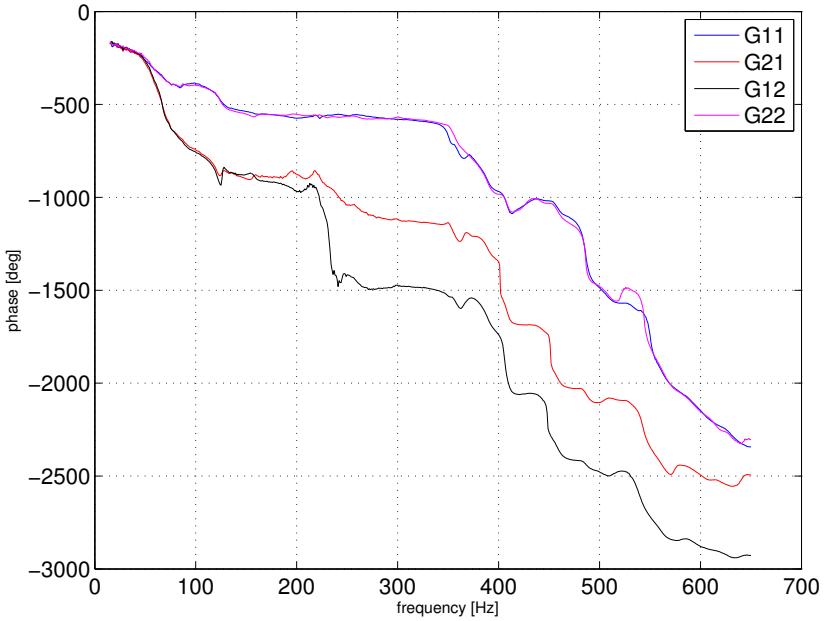
Result, 2×2 MIMO, shell sensors





Many resonances. Very high system order.

Decided to do ILC in the frequency domain

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ILC algorithm, FFT-based

Wanted reference chosen as either

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

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

Filters chosen as

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

$$Q_2(f) \equiv 1$$

Note: G^{-1} matrix inverse in the 2×2 case

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Convergence SISO

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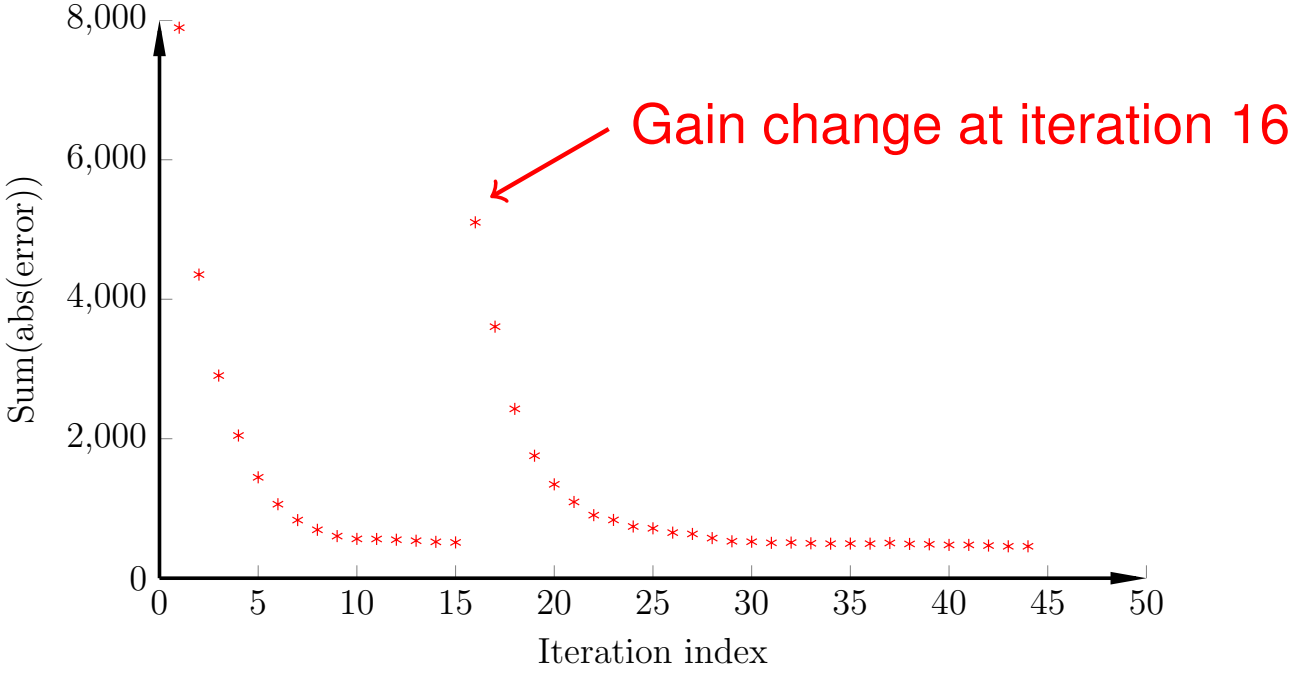
Robustness experiment - abrupt gain change



Convergence in 15 iterations

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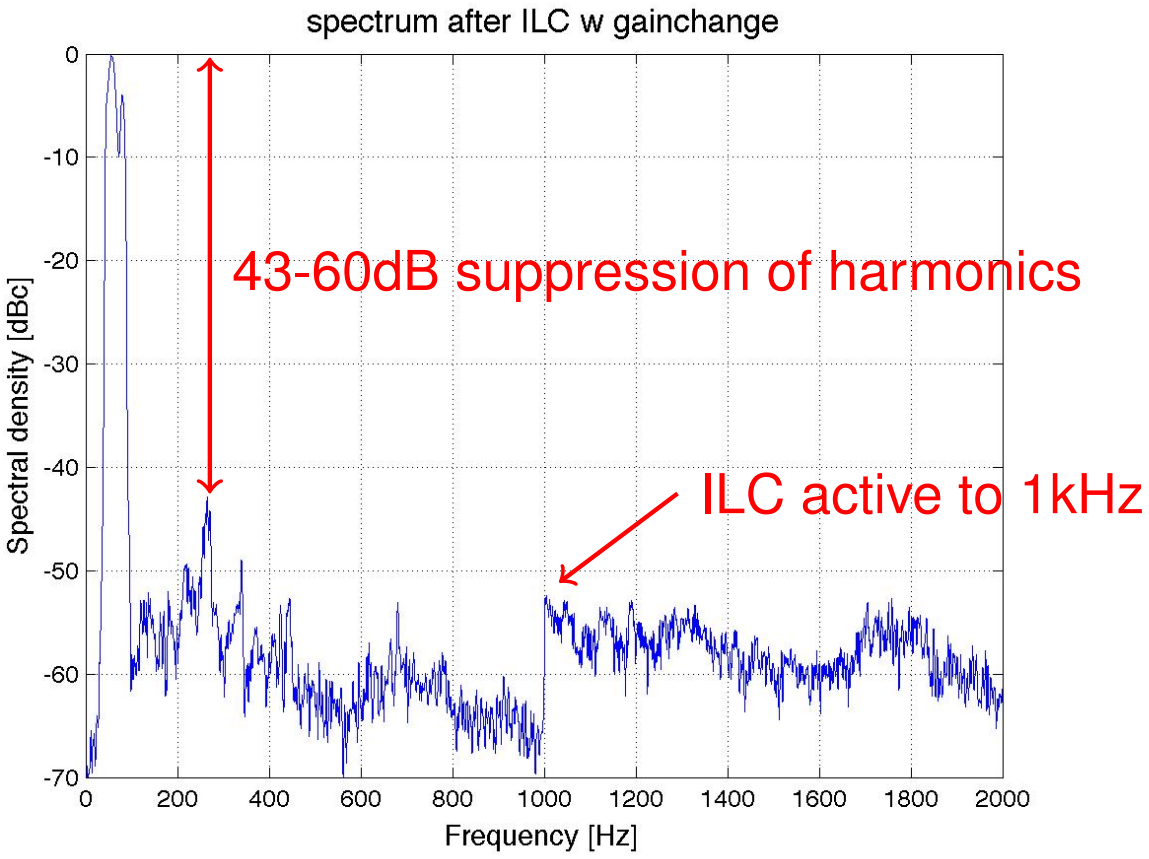
Spectrum after ILC - spring sensor



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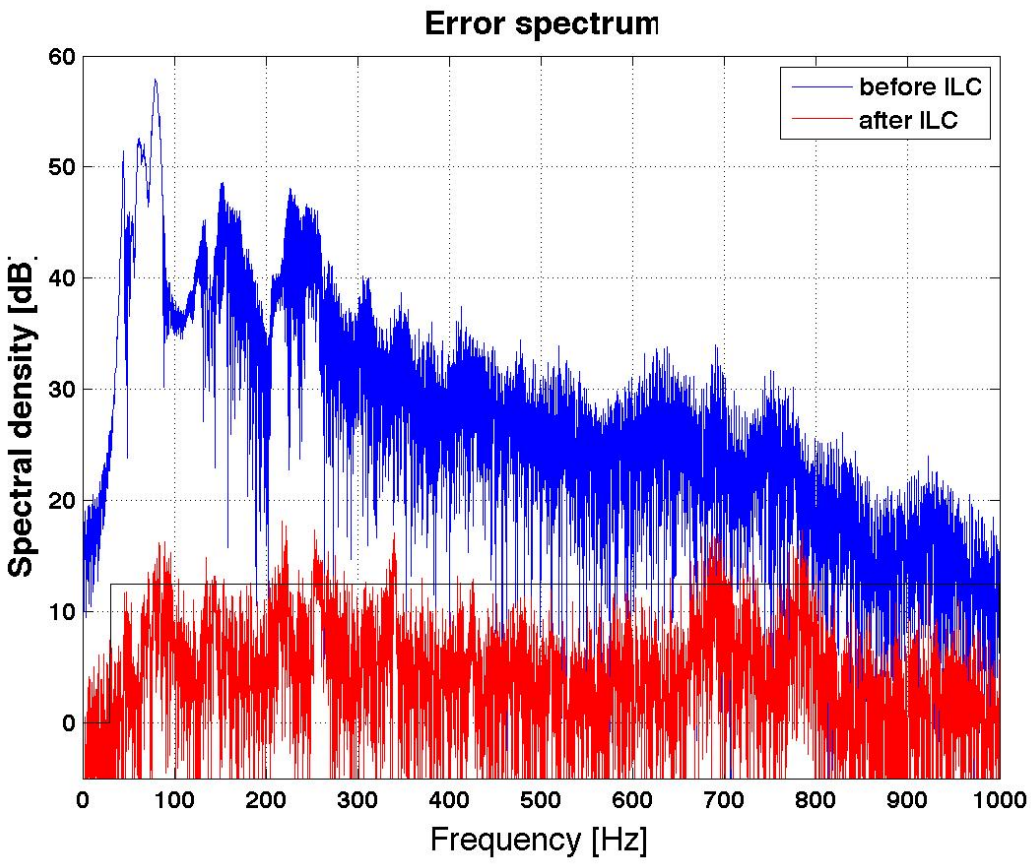
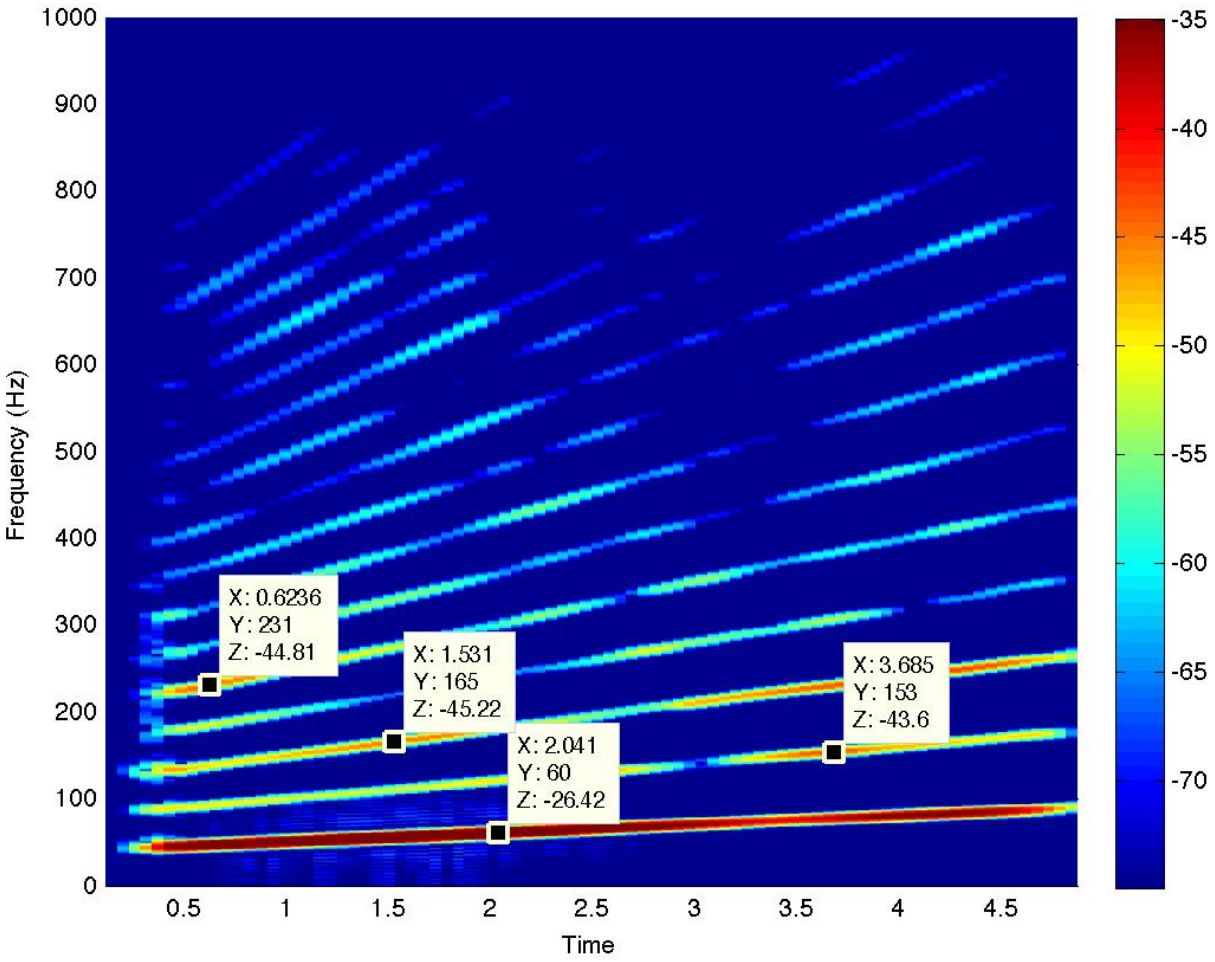
Error Spectrum SISO



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



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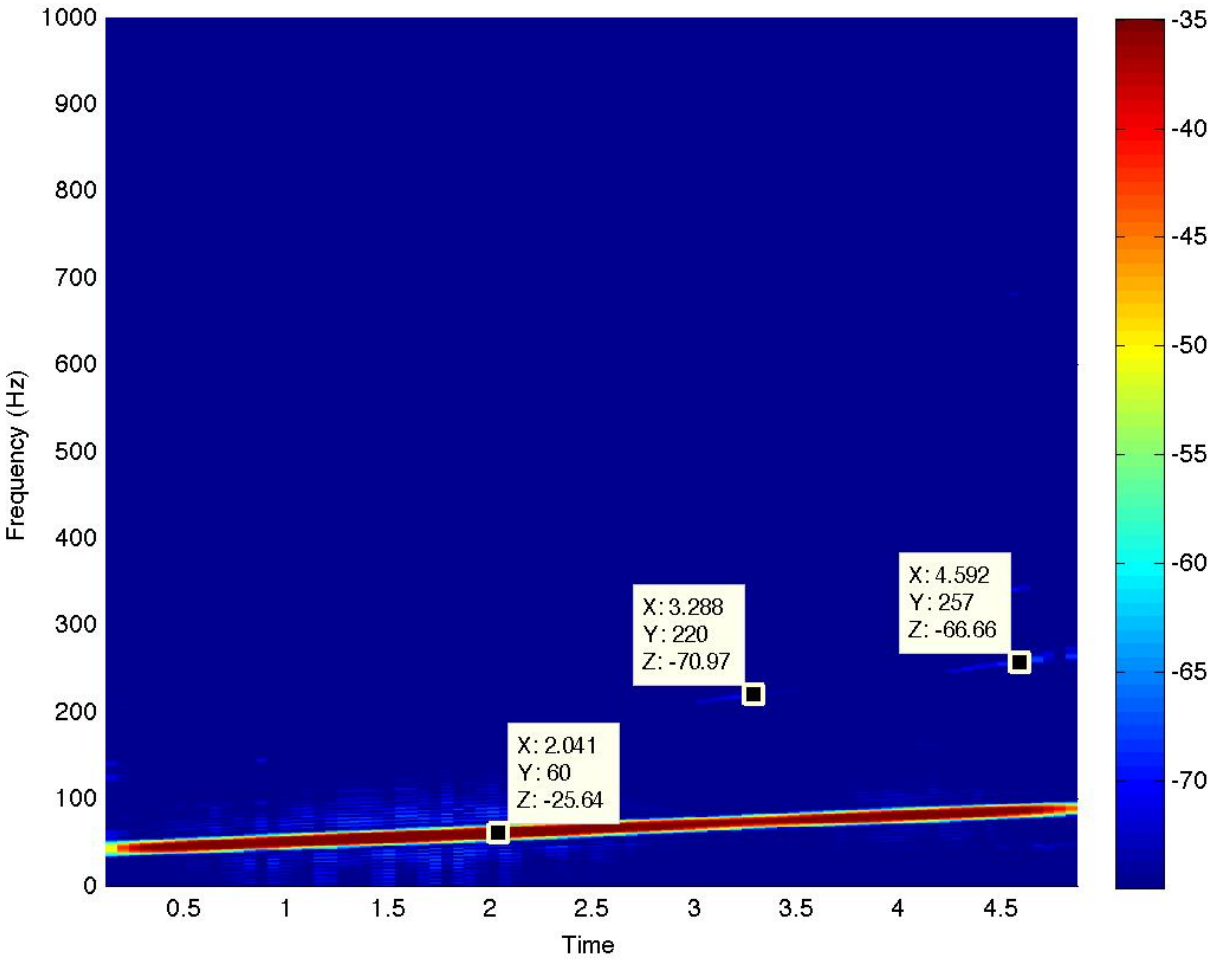
Spectrogram after ILC - spring sensor



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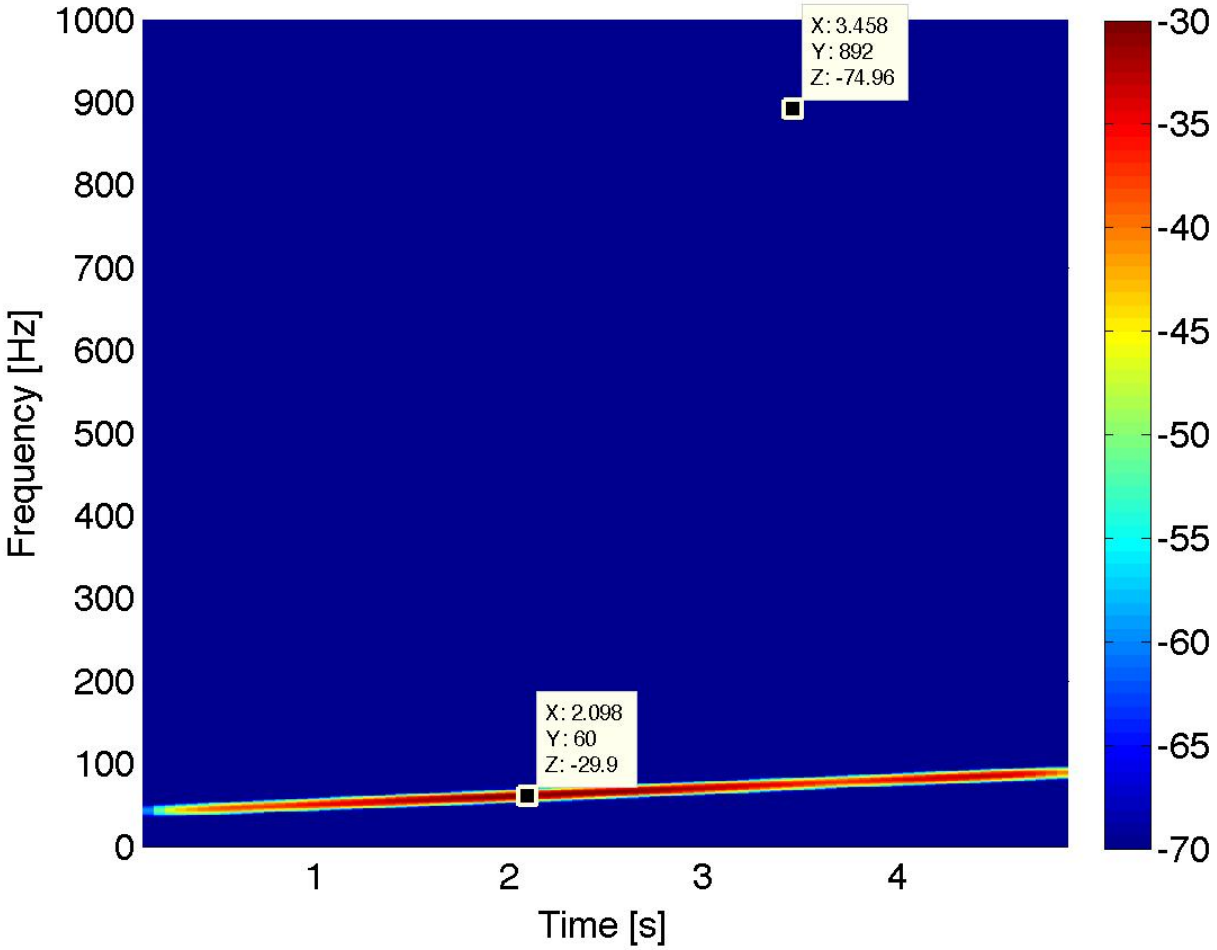
Same but with shell sensor



Very good results

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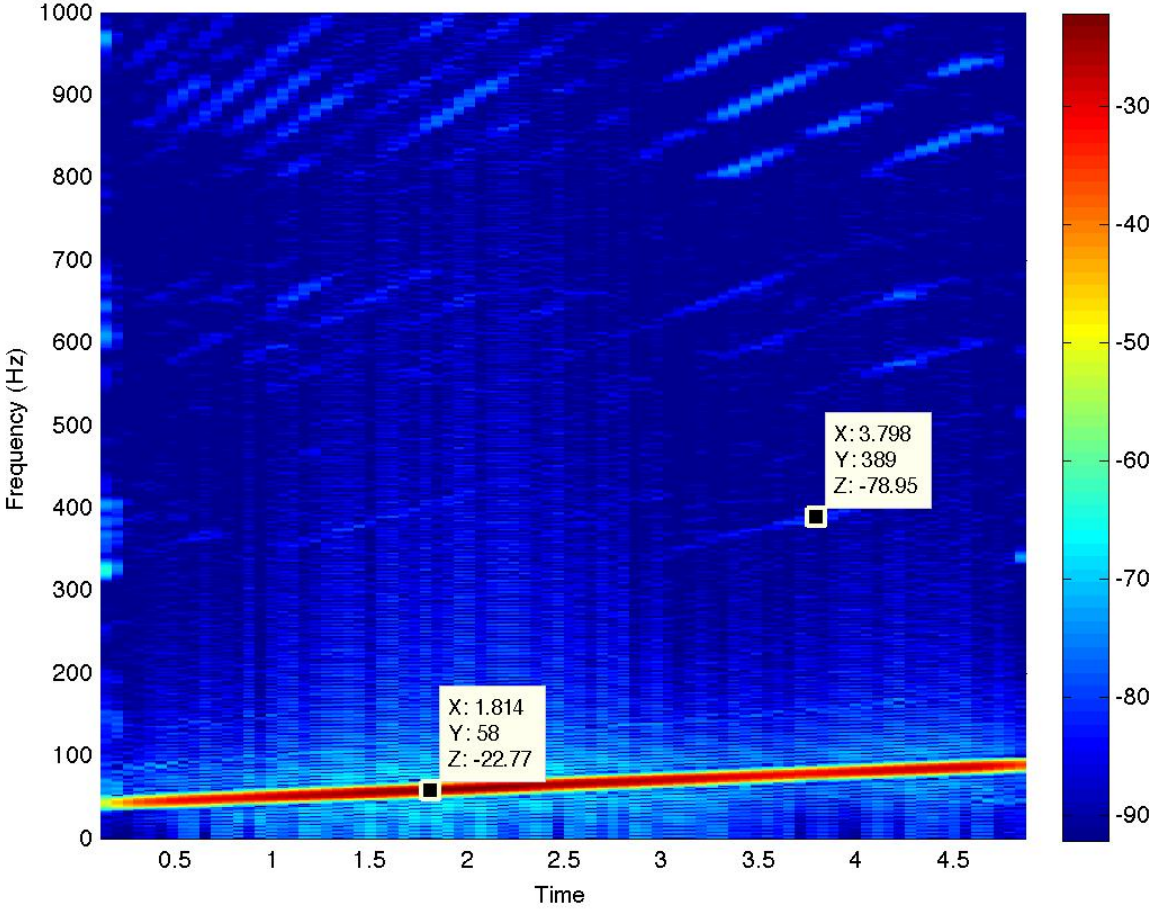
Detailed view

Detailed view, rescaled color range: 70dB.



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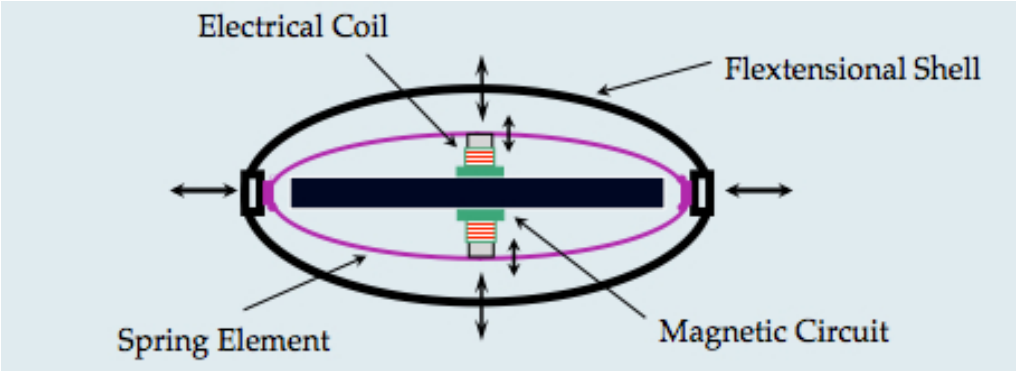
A Setback

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



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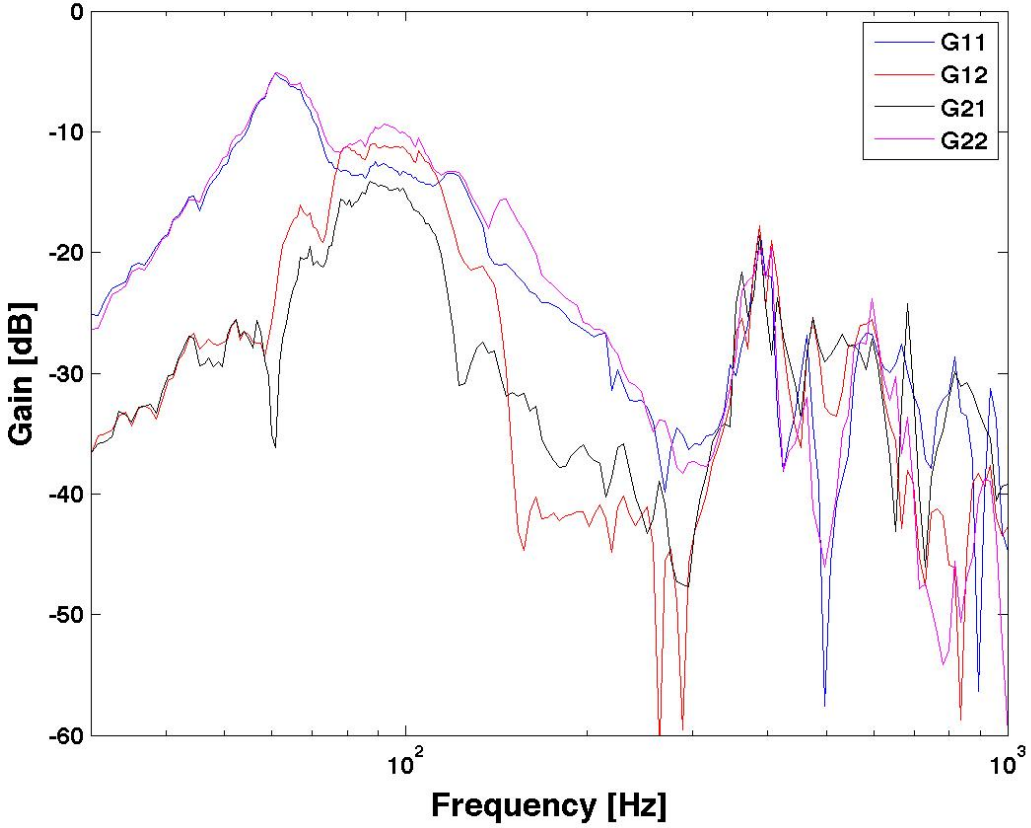
Double-sided control

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

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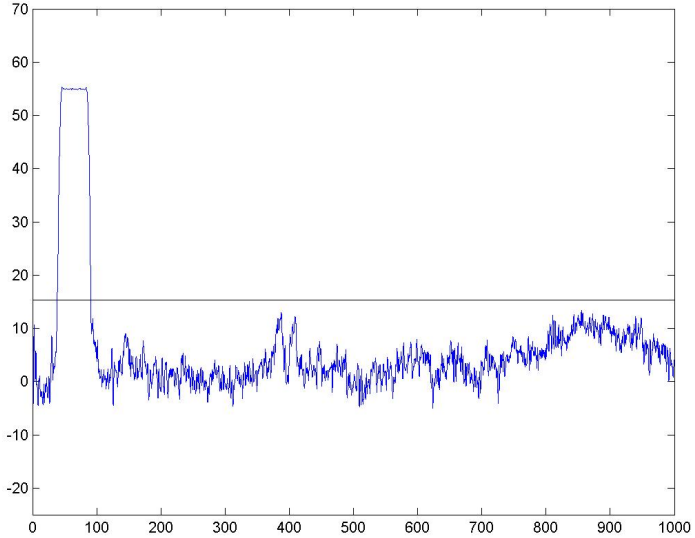
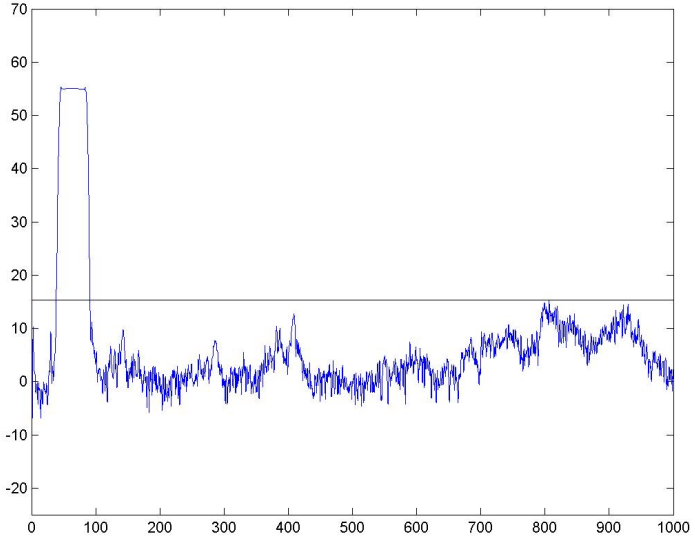
Spectrograms after ILC - double shell sensor

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





>40dB suppression

Note: Reference = constant amplitude chirp

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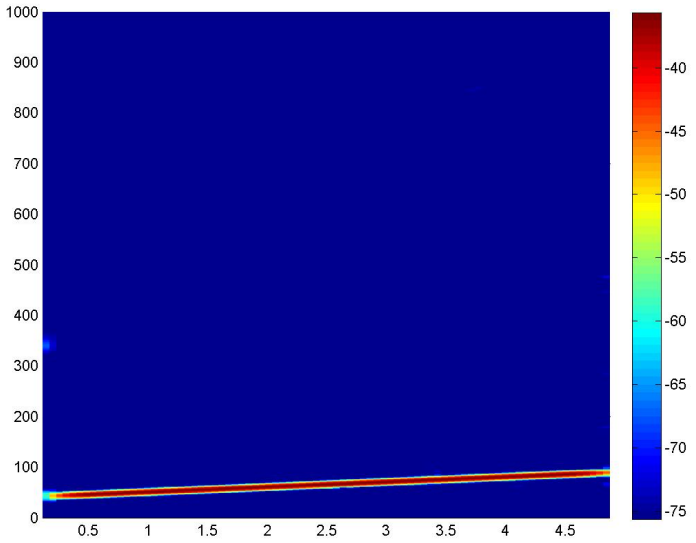
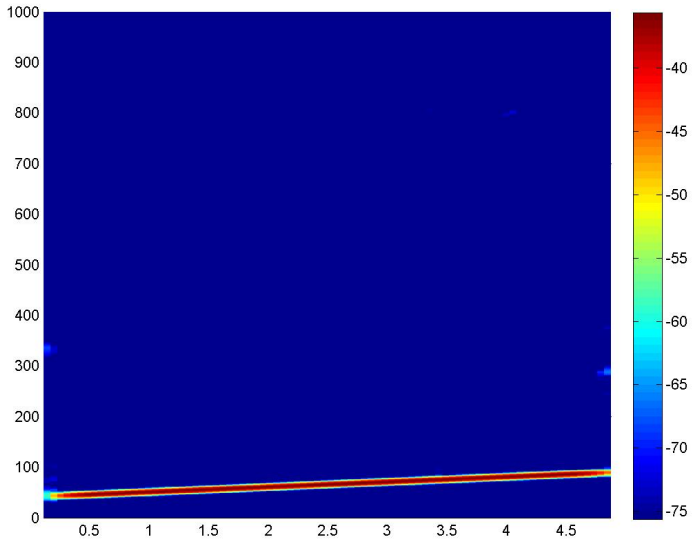
Spectrograms after ILC - double shell sensor

Spectrum on the accelerometers on the two sides





Both sides move according to wanted reference

40dB suppression

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Convergence - double shell sensors

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Convergence - double shell sensors

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Spectrogram - double shell sensors (50dB range!)

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Adaptation and robustifications

Several patent applications on adaptation and robustifications

Will not talk about this

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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

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Summary

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

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