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On Amplitude Estimation for High-Speed Atomic Force Microscopy

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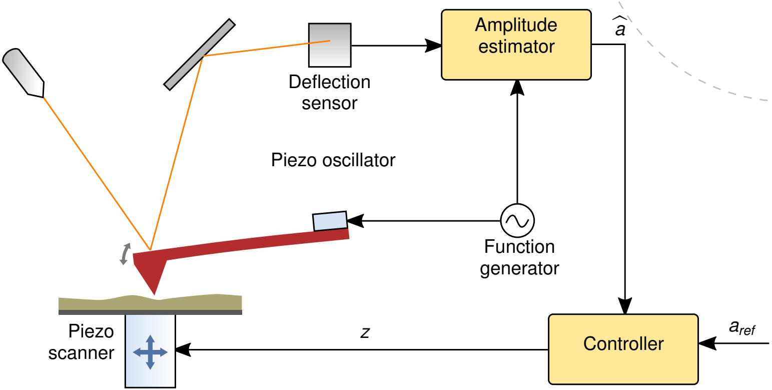
Atomic Force Microscopy (AFM) – AM Control Loop



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Atomic Force Microscopy (AFM) – AM Control Loop

Typical amplitude demodulator techniques (such as lock-in amplifier)

- convergence time 10 to 100+ cycles
- too slow for high-speed AFM

Main Results

Two main results:

— Comparison of existing amplitude estimators used in AFM.

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— Comparison of existing amplitude estimators used in AFM.

— Proposal of new amplitude est. technique from Ioannou and Sun (1996):

- Lyapunov-based parameter estimator

Problem Formulation

Estimate $a(t)$ in

$$s(t) = a(t)\sin(\omega_0 t + \phi) + w(t). \tag{1}$$

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Subject to the following requirements:

— High bandwidth
— Damped high-frequency response (resonants)
— Low complexity

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Outline

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Amplitude Estimation Techniques

Compare:

— Peak detection
— RMS-to-DC
— Peak hold
— Coherent
— Lock-in Amp.
— HB Lock-in Amp.
— Kalman filter
— Lyapunov

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$$x_k = \max\left(s_k,\, \widehat{a}_{k-1}\right)$$
$$\widehat{a}_k = H_{lp} x_k,$$

where H_{lp} is a low-pass filter with gain $0 \ll K < 1$.

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$$x_k = \mathrm{SH}(|s_k|, s_{k\perp})$$
$$\widehat{a}_k = H_{lp} x_k,$$

where $s_{k\perp}$ is a 90° phase-shifted version of s_k, $\mathrm{SH}(\cdot,\cdot)$ is a sample and hold function.

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$$
\begin{aligned}
i_k &= H_{lp} I_k \\
q_k &= H_{lp} Q_k \\
\widehat{a}_k &= 2\sqrt{i_k^2 + q_k^2},
\end{aligned}
$$

where

$$
\begin{aligned}
I_k &= s_k \sin(\omega_0 t_k) \\
Q_k &= s_k \cos(\omega_0 t_k).
\end{aligned}
$$

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$$\dot{\mathbf{x}} = \gamma \mathbf{c} y$$
$$y = H_{lp}(s - \mathbf{c}\mathbf{x})$$
$$\widehat{a} = \|\mathbf{x}\|_2,$$

where $\mathbf{c} = [\sin(\omega_0 t), \cos(\omega_0 t)]$.

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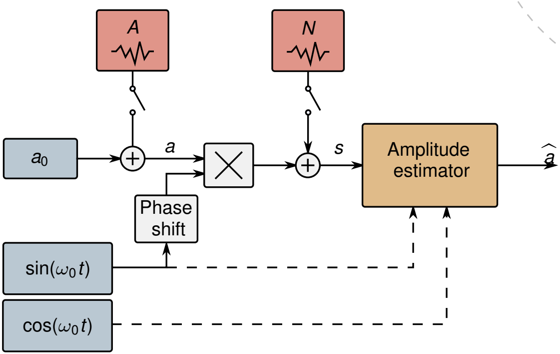
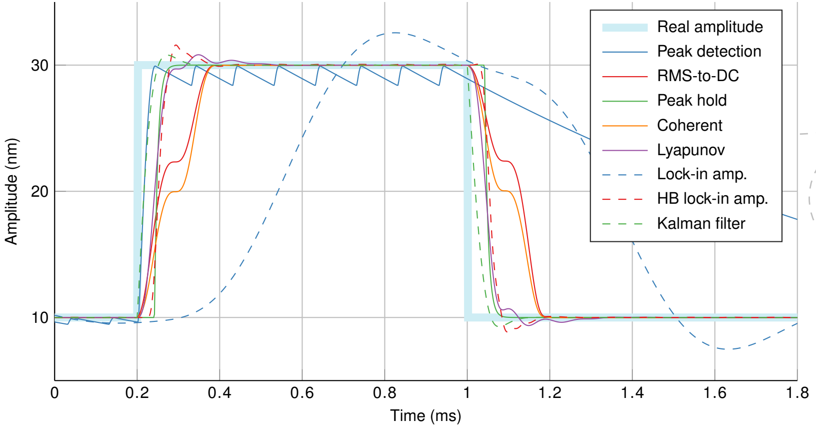
Simulation Setup



Results



Step-response

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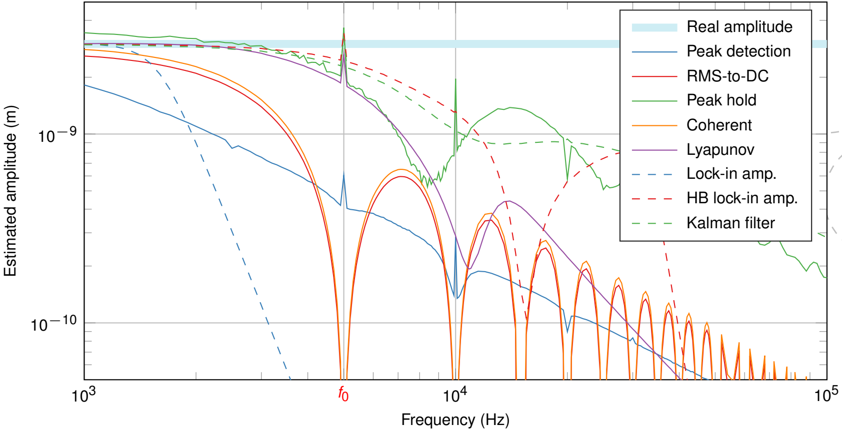
Results



Amplitude frequency response with measurement noise.

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Results

Amplitude estimation properties.
Carrier wave frequency 5 kHz.

Technique	Convergence time	Bandwidth (kHz)	Bias (pm)	Standard deviation (pm)	Phase estimation	Reference sinusoidals required	Accurate timing necessary
Peak detection	Exponential (fast up/slow down)	1.4	269	160	No	No	No
RMS-to-DC	Finite time (T_0)	2.9	12	14	No	No	Yes
Peak hold	Exponential (fast) + Constant ($\frac{1}{4}T_0$)	6.1	-3	480	No	No	No
Coherent	Finite time (T_0)	3.1	-5	14	Yes	No	Yes
Lyapunov	Exponential (fast)	5.8	0	19	Yes	Yes	No
Lock-in Amp.	Exponential (slow)	1.8	0	11	Yes	No	No
HB Lock-in Amp.	Exponential (fast)	8.9	7	27	Yes	Yes	No
Kalman filter	Exponential (fast)	7.7	0	29	Yes	Yes	No

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Lyapunov Experiment: Frequency Response

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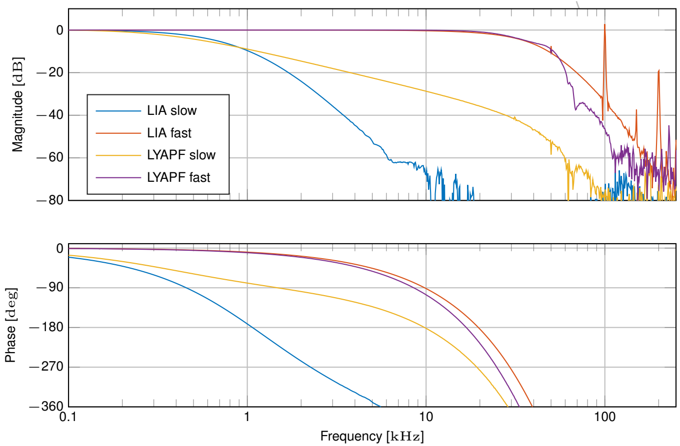
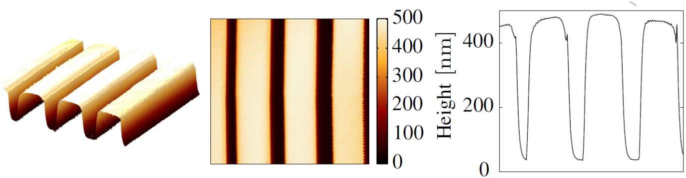


Preliminary result, thanks to Michael G. Ruppert and David M. Harcombe (UON).

Lyapunov Experiment: AFM



(a) 3D Image (b) 2D Image (c) Cross-section

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Conclusion

Simplest: Peak detection (but really bad)

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Fastest: HB Lock-in Amplifier & Kalman Filter

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Most accurate: Kalman Filter

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Best bandwidth/complexity trade-off: Lyapunov (new)?

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Questions?

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References

P A Ioannou and J Sun. *Robust adaptive control*. Prentice Hall, Upper Saddle River, NJ, 1996.

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